# Hunt for the Quark Gluon Plasma


The Quark Gluon Plasma as an Unicorn.
Experimentalists are the hunters, so....“All theorists are...”

# QCD at nonzero temperature

$T \sim 0$: Hadronic resonance gas.

$T \to \infty$: "perturbative" QCD Andersen, Leganger, Strickland, & Su, 1105.0514

Near the critical temperature?

There must be *an* effective theory near $T_c$.

One example: matrix model of semi-QGP (near $T_c$)

Simple, *closely* related to lattice simulations

Moderate, not strong coupling (versus AdS/CFT...)

K. Kashiwa, S. Lin, V. Skokov & RDP, 1205.0545, 1206.1329, 1301.5344, 1301.7432 + 1306....

A. Dumitru, Y. Guo, Y. Hidaka, C. Korthals-Altes & RDP, 1205.0137, 1011.3820

RDP & Hidaka, 0803.0453, 0906.1751, 0907.4609, 0912.0940

RDP, ph/0608242, ph/0612191...

# What the lattice tell us

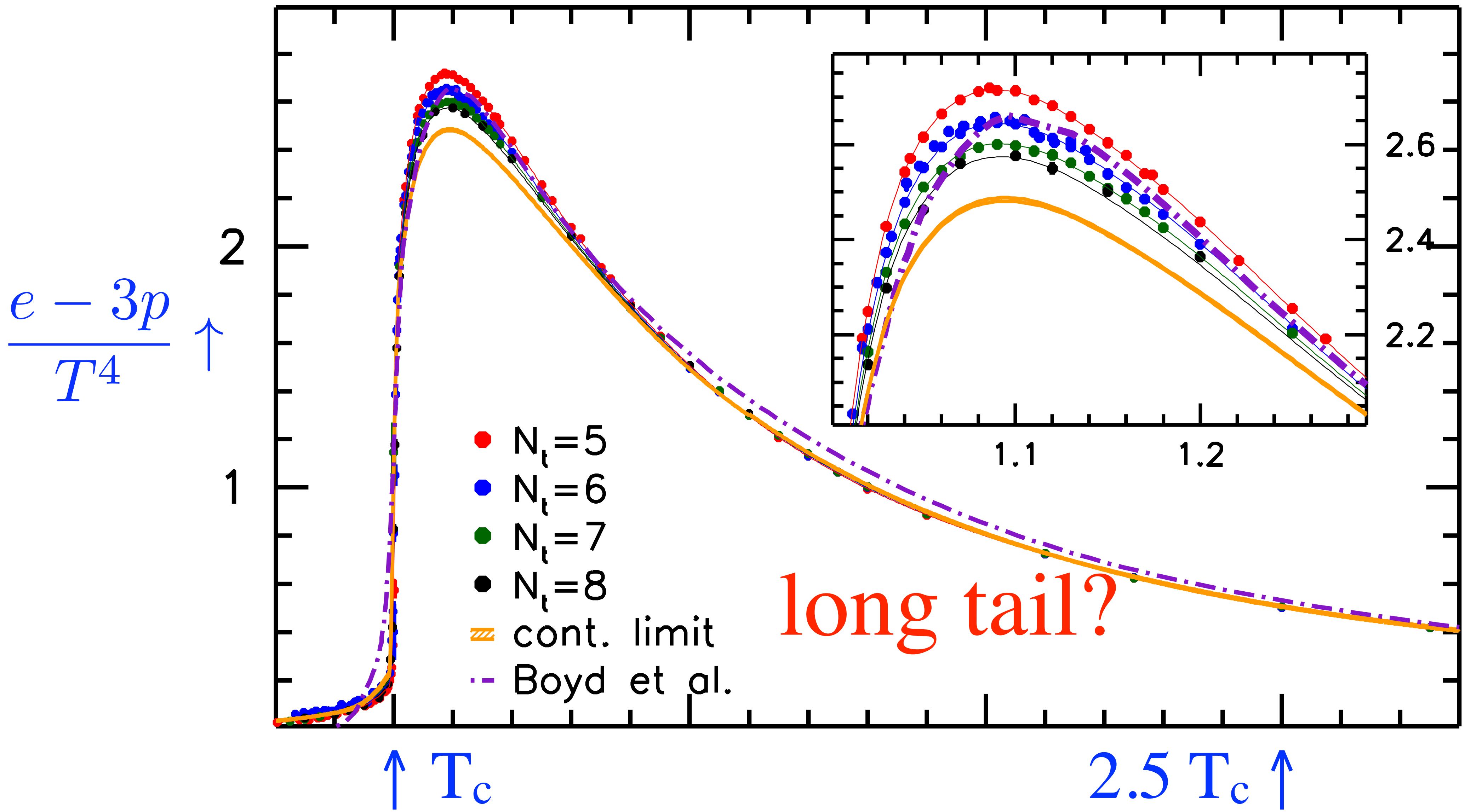
Hidden scaling of the pressure near $T_c$

(Resummed) perturbation theory

# Lattice: usual thermodynamics

"Pure" SU(3), no quarks. Peak in (e-3p)/$T^4$, just above $T_c$.

Borsanyi, Endrodi, Fodor, Katz, & Szabo, 1204.6184



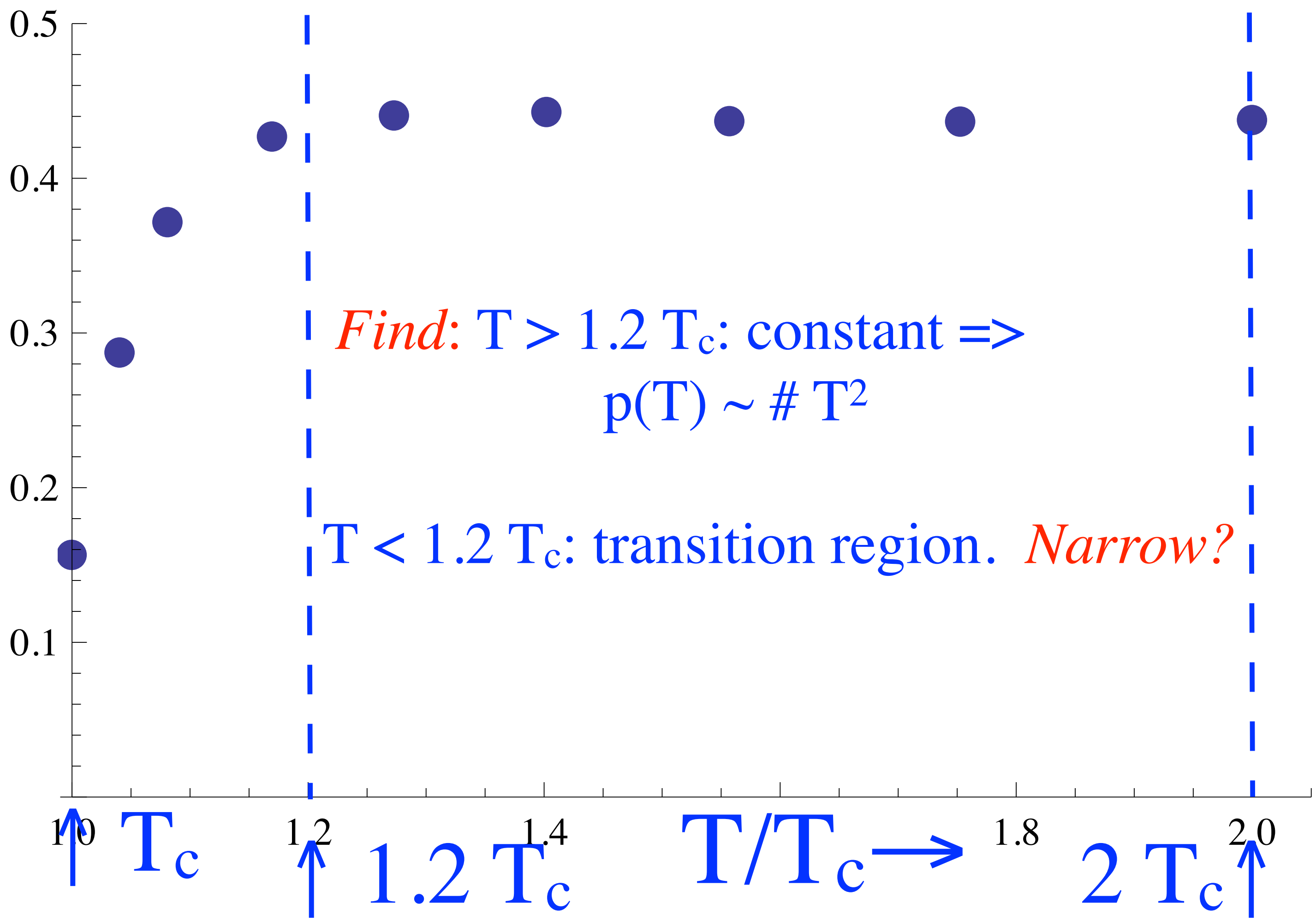
# Lattice: *hidden* scaling of the pressure

$(e-3p)/T^4 \times (T^2/T_c^2)$ *approximately* constant near $T_c$:

Meisinger, Miller, & Ogilvie, ph/0108009; RDP, ph/0608242

$$p(T) \approx \# \, T^2 (T^2 - c\, T_c^2) \,, \; c = 1.00 \pm .01$$

$$\frac{1}{8} \, \frac{e - 3p}{T^4} \, \frac{T^2}{T_c^2} \uparrow$$



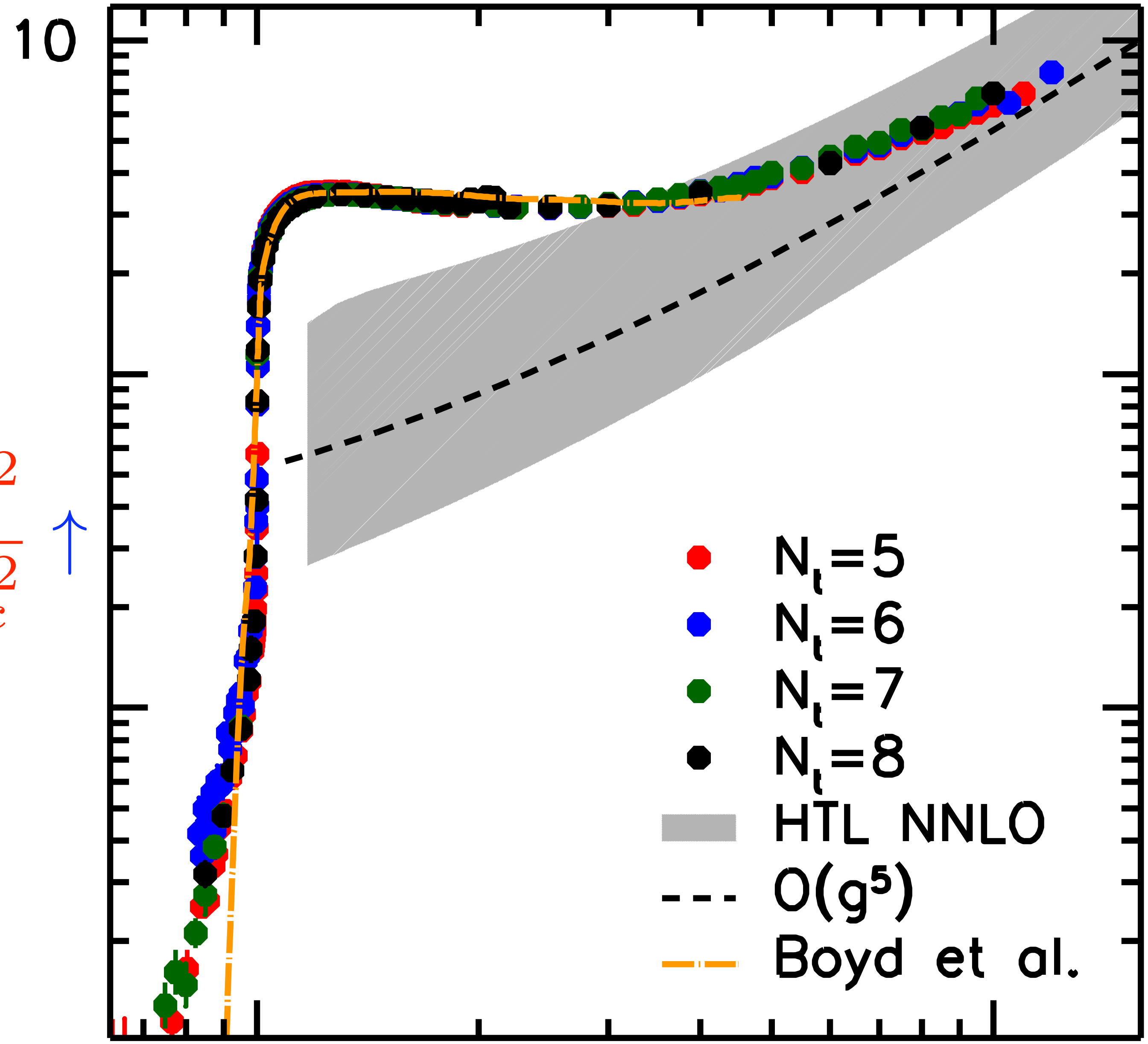

WHOT: Umeda, Ejiri, Aoki, Hatusda, Kanaya, Maezawa, Ohno, 0809.2842

# Lattice: hidden scaling, redux

$T_c \rightarrow 4\ T_c$:
For pressure, leading corrections to ideality, $T^4$, are *not* a bag constant, $T^0$, but ~ $T^2$ - ? Take as *given*.

$$\frac{e-3p}{T^4}\ \frac{T^2}{T_c^2} \uparrow$$

Borsanyi, Endrodi, Fodor, Katz, & Szabo, 1204.6184

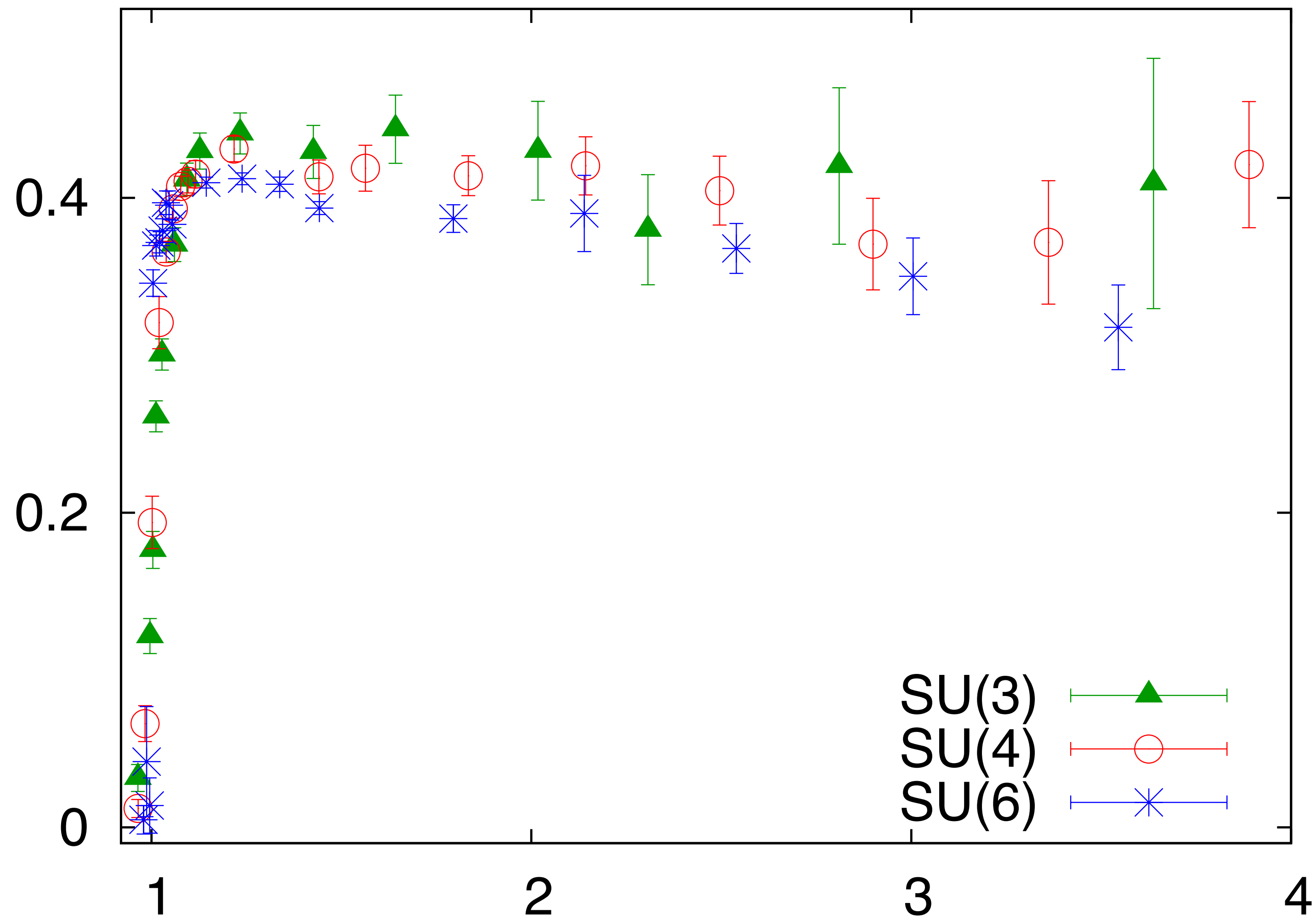



$\uparrow T_c$ $\qquad$ $10\ T_c \uparrow$

# Lattice: hidden scaling, 3 to 6 colors

Hidden scaling holds for N = 3, 4, 6:

$$\frac{1}{N^2-1}\;\frac{e-3p}{T^2\,T_c^2}\uparrow$$




$\uparrow$ $T_c$ $T/T_c \longrightarrow$ $4\,T_c$ $\uparrow$

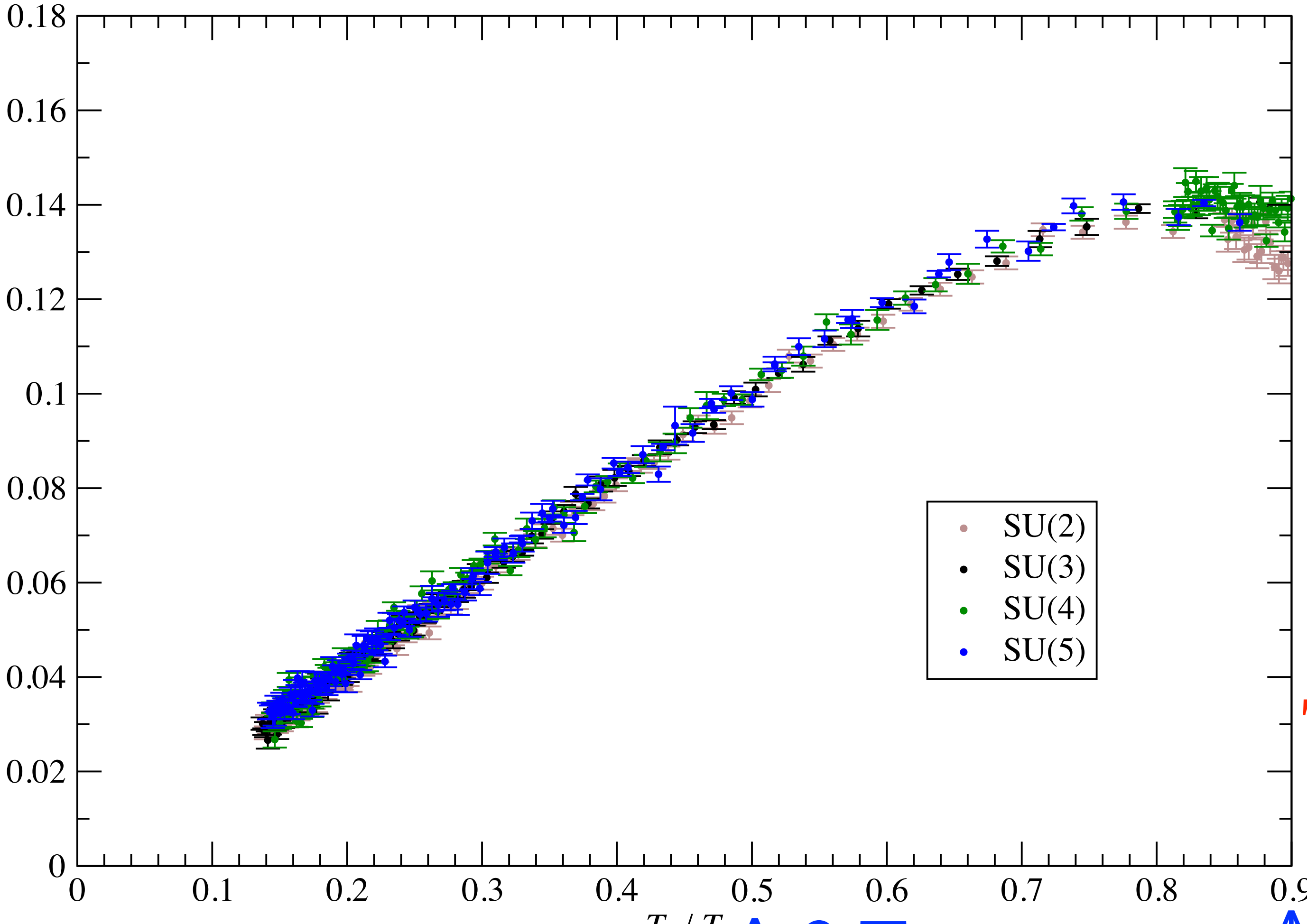
Datta & Gupta, 1006.0938

# Lattice: hidden scaling, SU(N) in 2+1 dimensions

In 2+ 1 dimensions, hidden scaling again ~ $T^2$: *not* a mass term, ~ $m^2$ T:

$$p(T) \approx \# \, T^2 (T - c\, T_c)\, , \; c \approx 1.$$

$$\frac{1}{N^2-1}\;\frac{e-2p}{T^3}\uparrow$$




$T_c/T \rightarrow$

$\uparrow$ 10 $T_c$ $\uparrow$ 2 $T_c$ $\uparrow$ 1.1 $T_c$

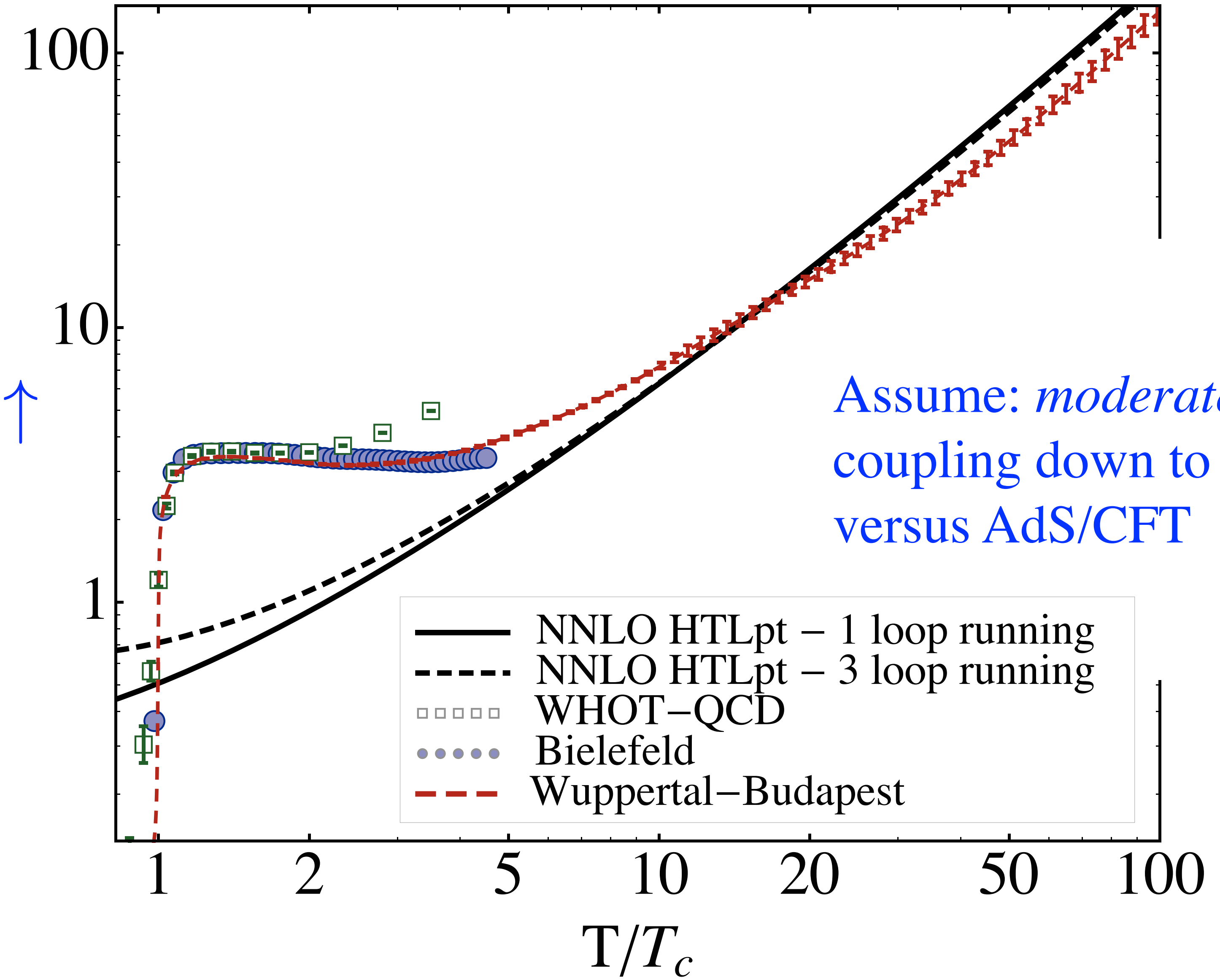
Caselle, Castagnini, Feo, Gliozzi, Gursoy, Panero, Schafer, 1111.0580

# Moderate coupling, down to $T_c$

QCD coupling is *not* so big at $T_c$, $\alpha(2\pi T_c) \sim 0.3$ (runs like $\alpha(2\pi T)$ )

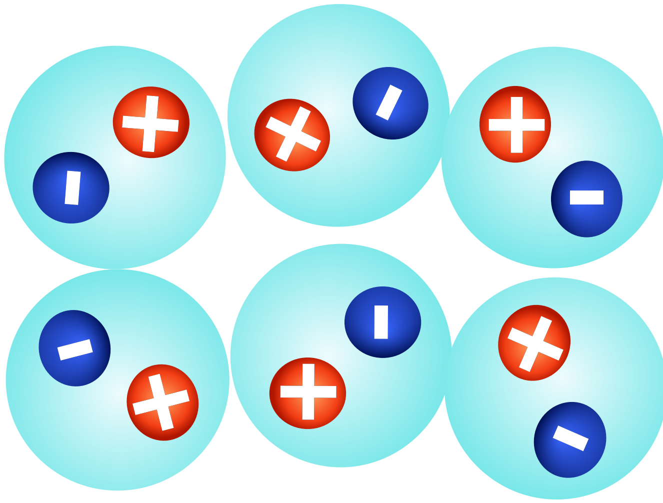
HTL perturbation theory at NNLO: Andersen, Leganger, Strickland, & Su, 1105.0514

$$\frac{e-3p}{T^4}\ \frac{T^2}{T_c^2} \uparrow$$

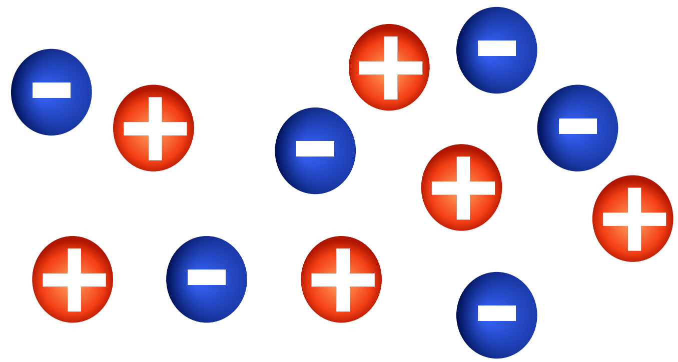



Assume: *moderate* coupling down to $T_c$ versus AdS/CFT

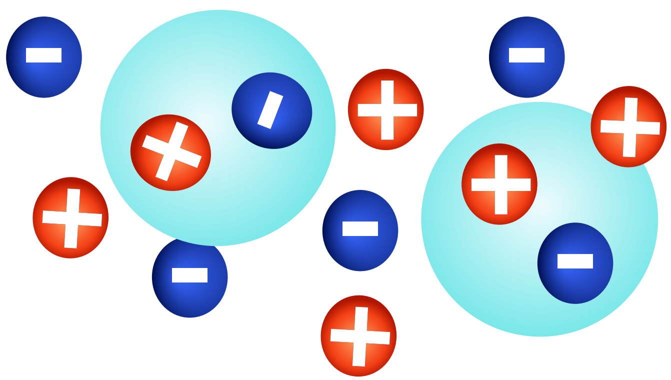
# Ionization in QED plasma



Neutral state $\rightsquigarrow$ atoms,
electric neutrality > atomic scales

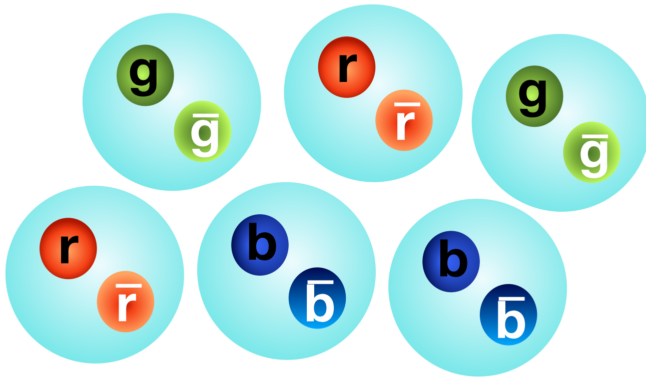


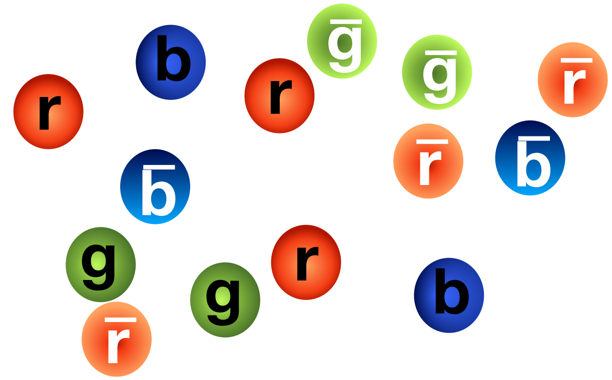
Completely ionized plasma $\rightsquigarrow$ plasma
with freely moving electric charges



Partially ionized plasma $\rightsquigarrow$ *partially* ionized plasma with atoms and electric charges

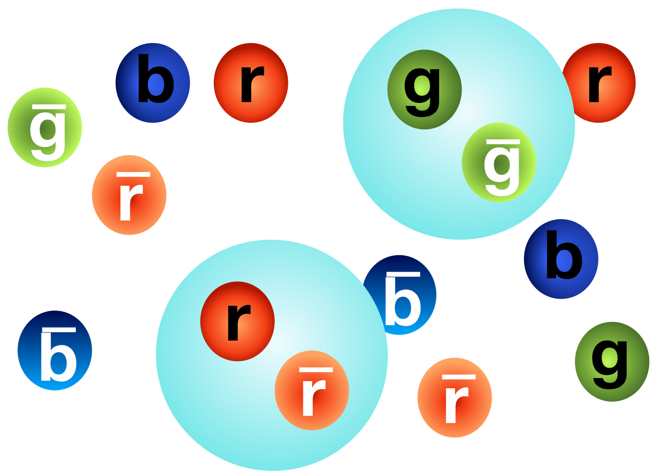
# Ionization in QCD plasma




Neutral state $\rightsquigarrow$ confined phase, color neutrality > hadronic scale

Completely ionized plasma $\rightsquigarrow$ perturbative QGP with freely moving charges



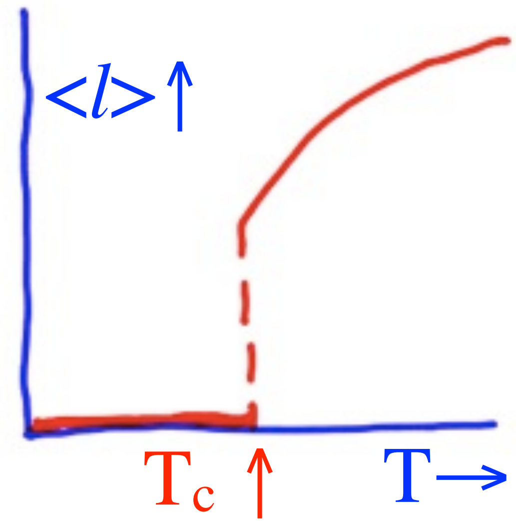

Partially ionized plasma $\rightsquigarrow$ *partial* ionization of color: hadrons and color charges; semi-QGP, nontrivial holonomy

# Z(N) symmetry and Polyakov Loops

**L** = SU(N) matrix, trace = Polyakov loop, *l*: $\ell = \dfrac{1}{N}\,\mathrm{tr}\,\mathbf{L}$

< *l* > measures color ionization: $< \ell > \sim \; \mathrm{e}^{-F_{\mathrm{test\;qk}}/T}$

Confinement => no ionization of color,
=> < *l* > = 0, T < $T_c$: Z(N) *symmetric* phase.
Color ionized above $T_c$, so
< *l* > ≠ 0, T > $T_c$, Z(N) broken

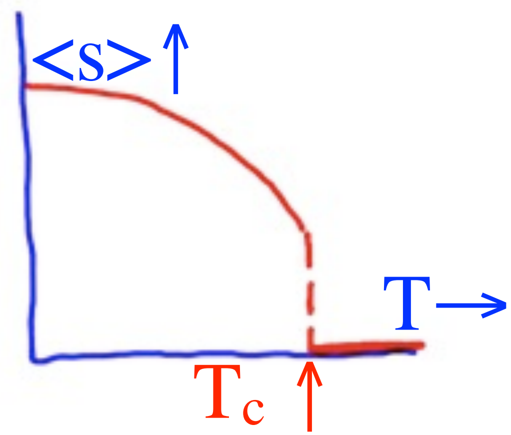



Z(N) symmetry *essential* to deconfinement in SU(N)

Svetitsky and Yaffe ’80:
SU(3) 1st order because of Z(3) symmetry:
Eff. Lag. of *loops* has cubic terms, $l^3 + (l^*)^3$.

Does *not* apply for N > 3.

Ordinary spins, s:



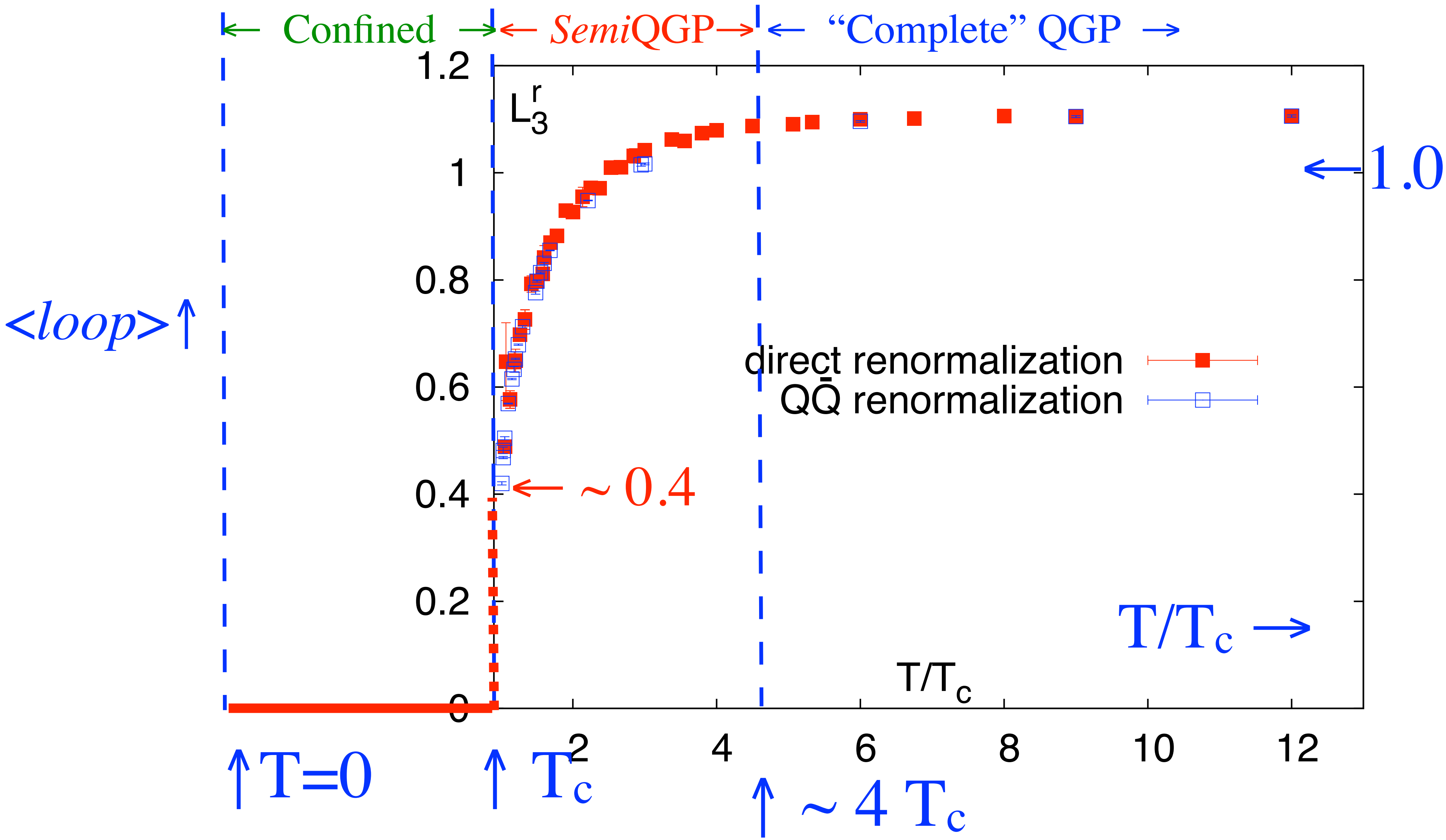

So why is deconfinement 1st order for *all* N ≥ 3?

# Polyakov loops from Lattice: pure Glue, no Quarks

Lattice: (*renormalized*) Polyakov loop. Strict order parameter

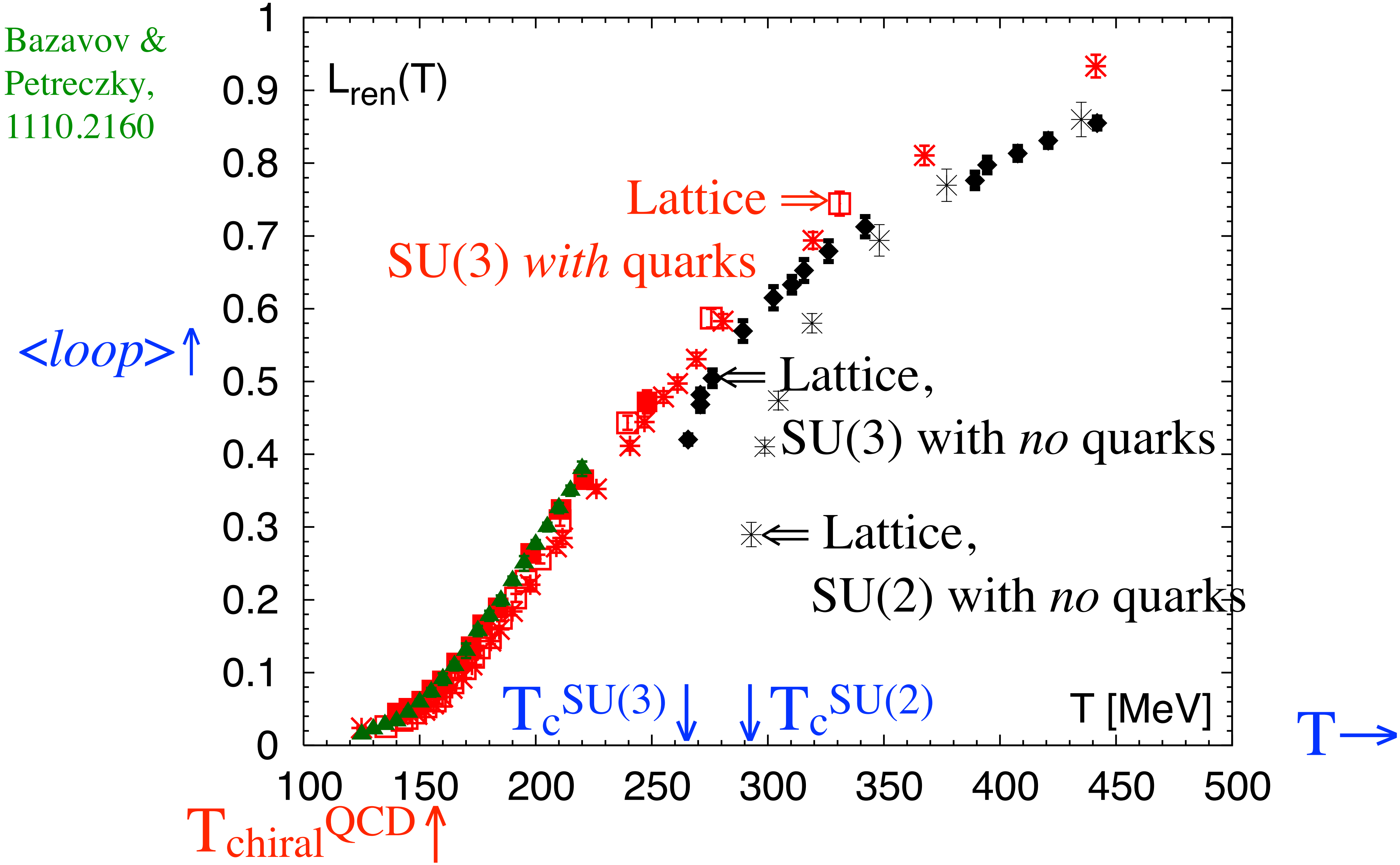
Three colors: Gupta, Hubner, Kaczmarek, 0711.2251.

Suggests *wide* transition region, like pressure, to ~ 4 $T_c$.



# Loop with, and without, quarks

Matrix Model: use *same* $T_c$ with quarks. Loop turns on below $T_c$.
Chiral transition is *not* tied to deconfinement. Like lattice results:

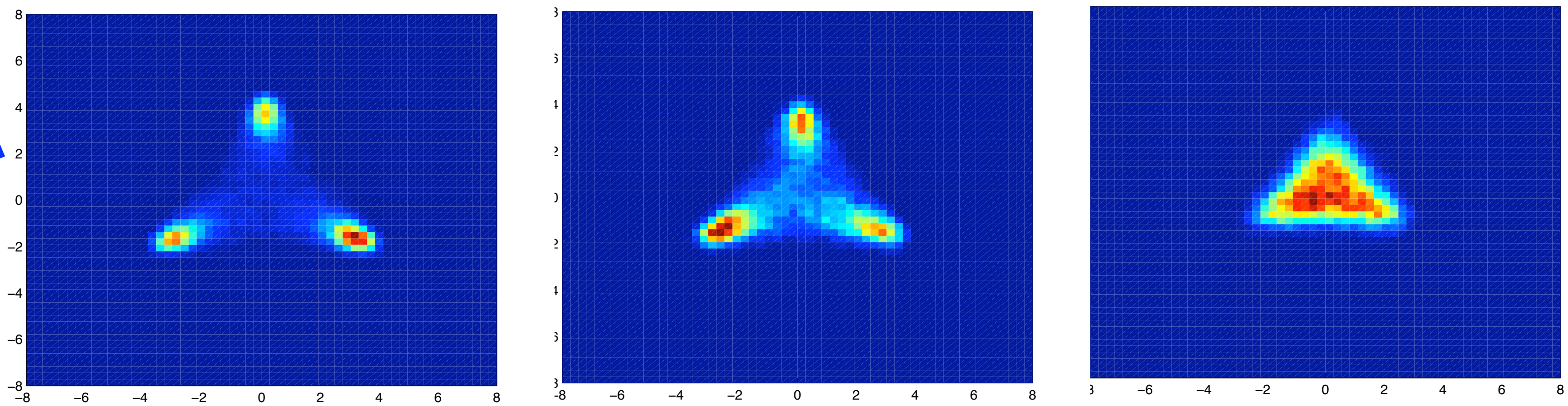


# Z(3) symmetry and 't Hooft loops

Lattice, A. Kurkela, unpub.'d: 3 colors, loop $l$ complex.

Distribution of loop shows Z(3) symmetry. Cannot ignore Z(3)!

Im $l$ ↑



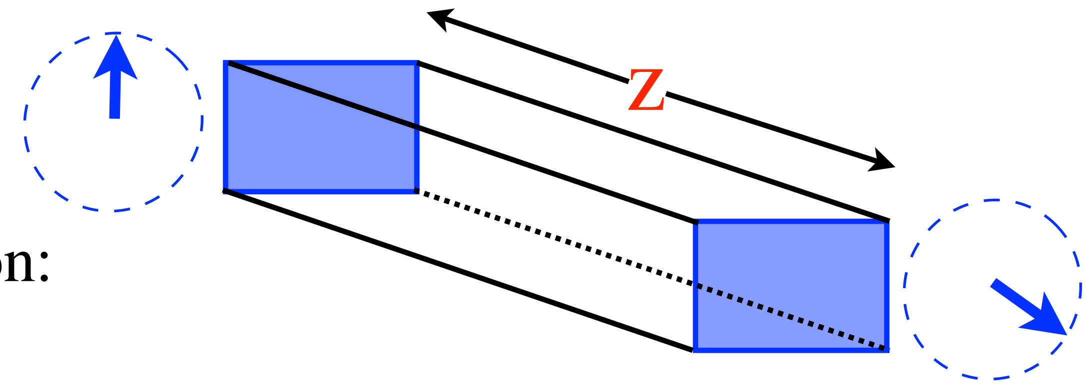
Re $l$ →

T >> $T_c$ T ~ $T_c$ T < $T_c$

Interface tension: box long in z.

Each end: distinct but *degenerate* vacua.

Interface forms, action ~ interface tension:




T > $T_c$: order-order interface = '*t Hooft loop*:

Measures response to *magnetic* charge

Korthals-Altes, Kovner, & Stephanov, hep-ph/9909516

$$Z \sim e^{-\sigma_{int} V_{tr}}$$

Also: *if* transition 1st order, order-*dis*order interface tension *at* $T_c$ .

# Lattice: 't Hooft loops σ near $T_c$

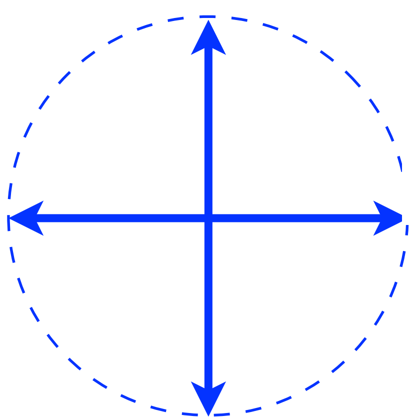
Lattice: de Forcrand & Noth, lat/0510081. σ ~ universal with N

Semi-classical σ : Giovanengelli & Korthals-Altes ph/0102022; /0212298; /0412322: *GKA '04*

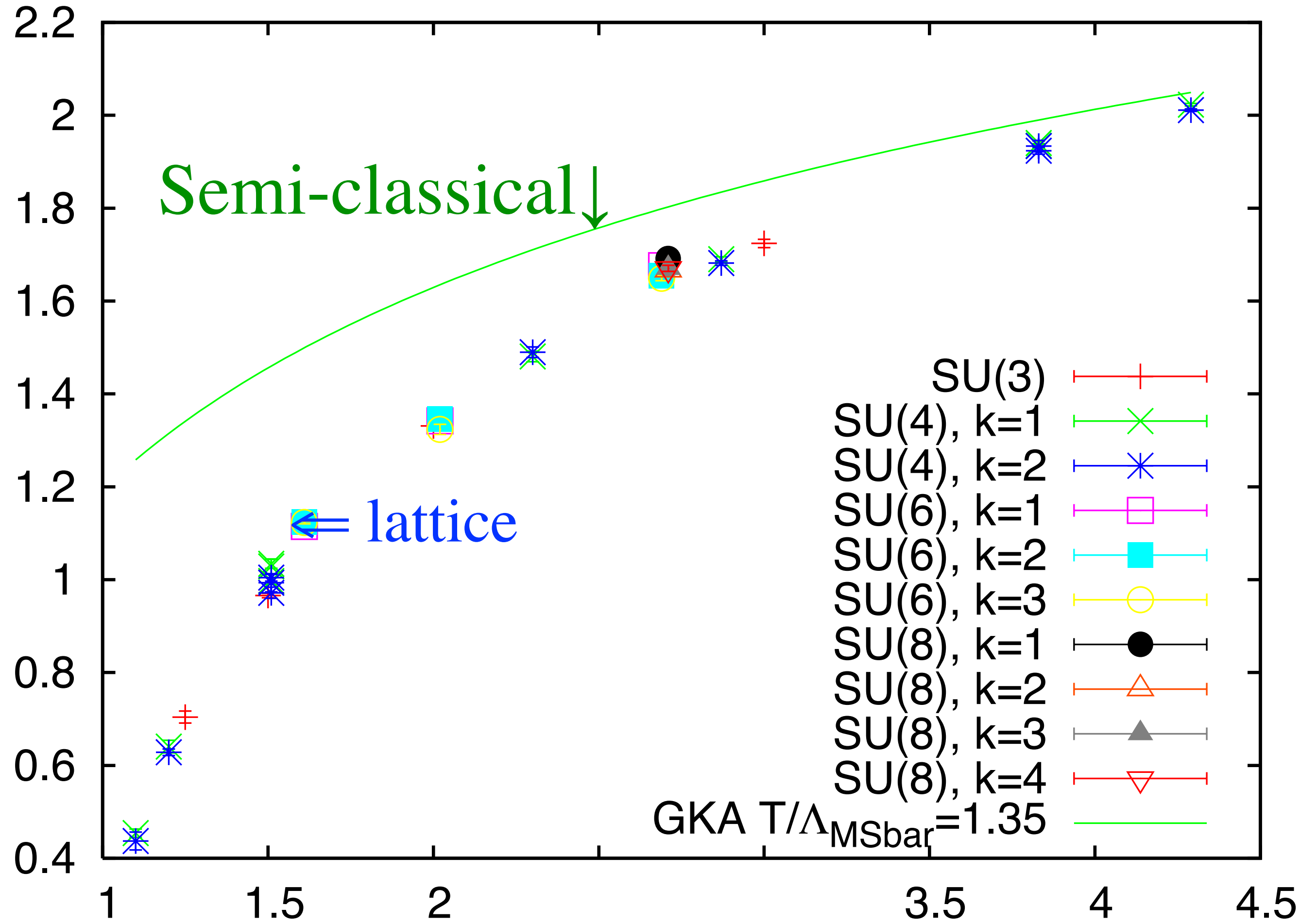
Above 4 $T_c$, semi-class σ ~ lattice. Below 4 $T_c$, lattice σ << semi-classical σ.

Interface tensions *small* at $T_c$ for all N

$$\frac{\sigma_k}{T^2\,k(N-k)} \uparrow$$



N = 4




↑ $T_c$ $T/T_c$ → 4.5 $T_c$ ↑

# Other models for the "s" QGP,

From ~ $T_c$ to ~ a few times $T_c$: "s" = strong? Strong coupling or...

# Other models

Massive quasiparticles: Peshier, Kampfer, Pavlenko, Soff '96...Peshier & Cassing, ph/0502138 Bratkovskaya + ...1101.5793 Castorina, Miller, Satz 1101.1255 + ....

Mass decreases pressure, so adjust m(T) to fit p(T): three parameters.

$$p(T) = \# T^4 - m^2 T^2 + \ldots$$

Polyakov loops: Fukushima ph/0310121...Hell, Kashiwa, Weise 1104.0572

Effective potential of Polyakov loops.
Potential has five parameters
1 variable, trace of (thermal) Wilson line, **L**
Matrix model for SU(N): N-1 eigenvalues of **L**.

$$V_{eff}(T) \sim m^2 \ell^* \ell + T \log f(\ell^* \ell)$$

$$m^2 = T^4 \sum_{i=0}^{3} a_i (T_c/T)^i$$

AdS/CFT: Gubser, Nellore 0804.0434...Gursoy, Kiritsis, Mazzanti, Nitti, 0903.2859

Add potential for dilaton, φ, to fit pressure.
Only infinite N, two parameters

$$V(\phi) \sim \cosh(\gamma\phi) + b\,\phi^2$$

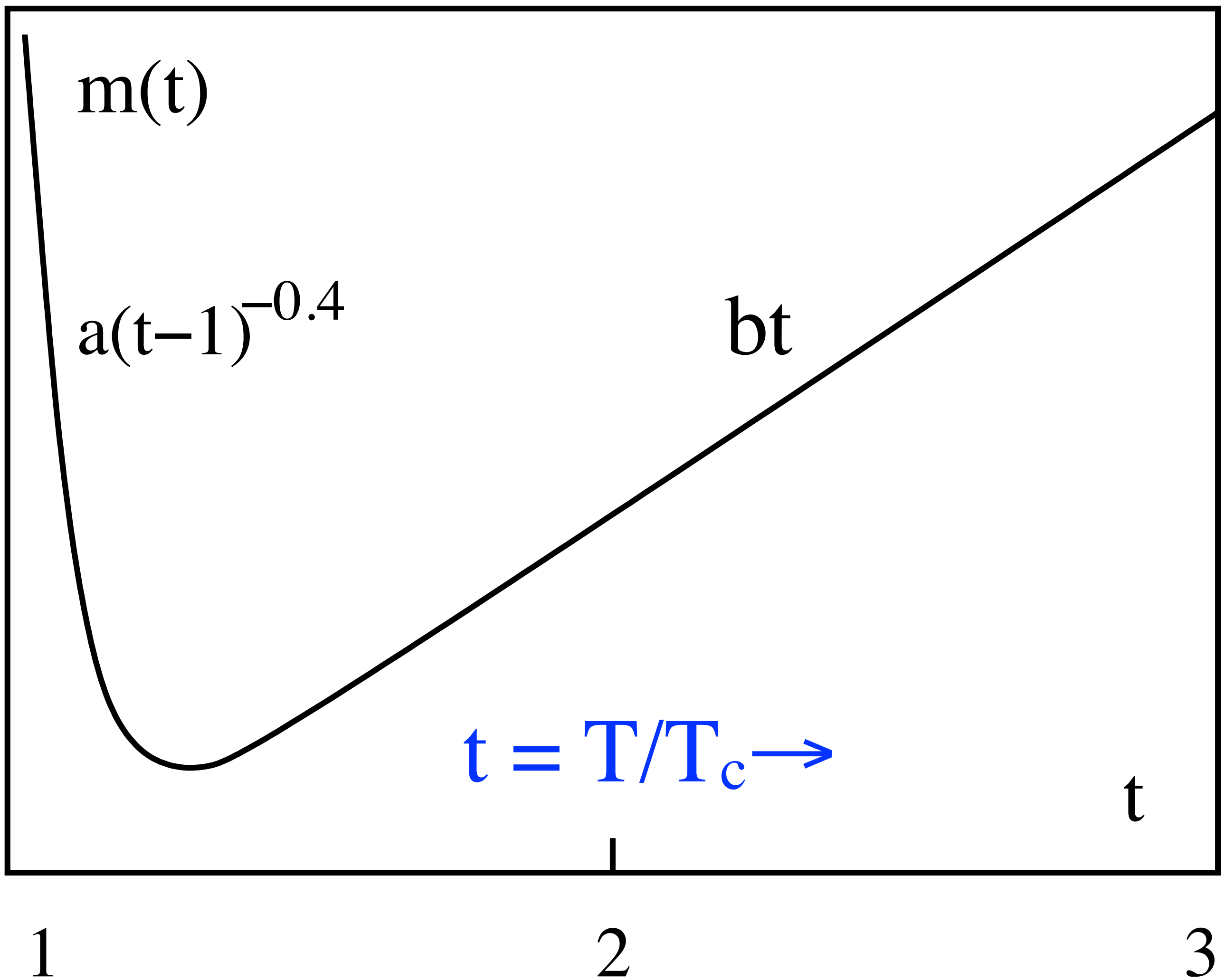
# Quasiparticle Model

Castorina, Miller, Satz 1101.1255:

Since peak in $(e-3p)/T^4$ is near $T_c$, involved form for quasiparticle mass:

$$m_{\text{gluon}}(T) = a(t-1)^{-0.41} + bt \; ; \; t = T/T_c$$

m(t) ↑



# Yet more models

Linear model of Wilson lines: Vuorinen & Yaffe, ph/0604100;
de Forcrand, Kurkela, & Vuorinen, 0801.1566; Zhang, Brauer, Kurkela, & Vuorinen, 1104.0572

$$V_{eff}(\mathbf{Z}) = m^2\ \mathrm{tr}\mathbf{Z}^\dagger\mathbf{Z} + \kappa\,(\det\mathbf{Z} + c.c.) + \lambda\,\mathrm{tr}(\mathbf{Z}^\dagger\mathbf{Z})^2 + \ldots$$

Narrow transition region: Braun, Gies, Pawlowski, 0708.2413;
Marhauser & Pawlowski, 0812.1444; Braun, Eichhorn, Gies, & Pawlowski, 1007.2619

Deriving effective theory from QCD:

Monopoles: Liao & Shuryak, ph/0611131, 0706.4465, 0804.0255, 0804.4890, 0810.4116, 1206.3989; Shuryak & Sulejmanpasic, 1201.5624

Dyons: Diakonov & Petrov, th/0404042, 0704.3181, 0906.2456, 1011.5636

Bions: Unsal, 0709.3269; Simic & Unsal 1010.5515; Poppitz, Schaefer, & Unsal 1205.0290

# Matrix model: two colors

Just expand about *constant*, diagonal $A_0$

*Necessary* to include physics of Z(N) vacua

Deconfining transition 2nd order for two colors

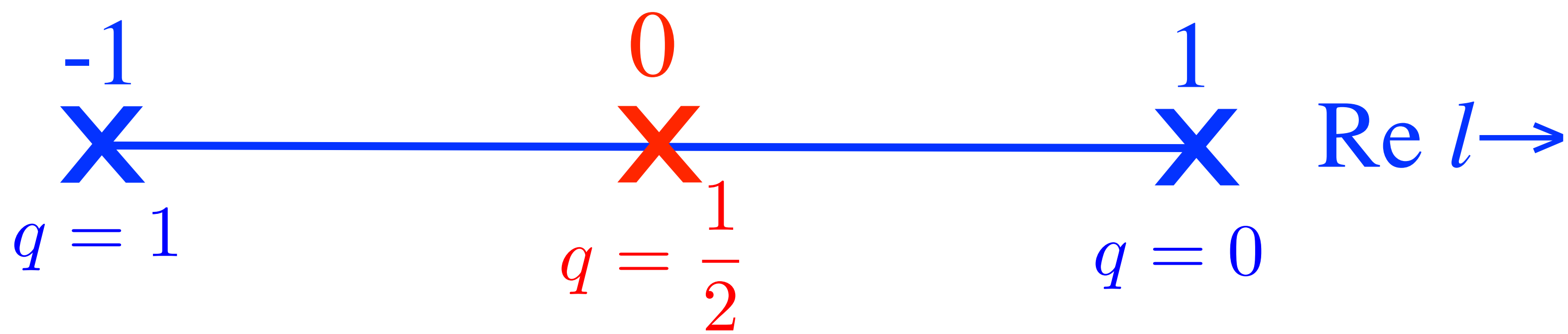
A. Dumitru, Y. Guo, Y. Hidaka, C. Korthals-Altes & RDP, 1205.0137

# Matrix model: SU(2)

*Simplest* possible approx.: model *constant* gauge transf.'s with *constant* $A_0 \sim \sigma_3$:

$$A_0^{cl} = \frac{\pi T}{g} q\, \sigma_3 \ , \ \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad \mathbf{L}(q) = \begin{pmatrix} \mathrm{e}^{i\pi q} & 0 \\ 0 & \mathrm{e}^{-i\pi q} \end{pmatrix}$$

Loop $l$ real. Z(2) degenerate vacua q = 0 and 1: $\qquad \ell = \cos(\pi q)$



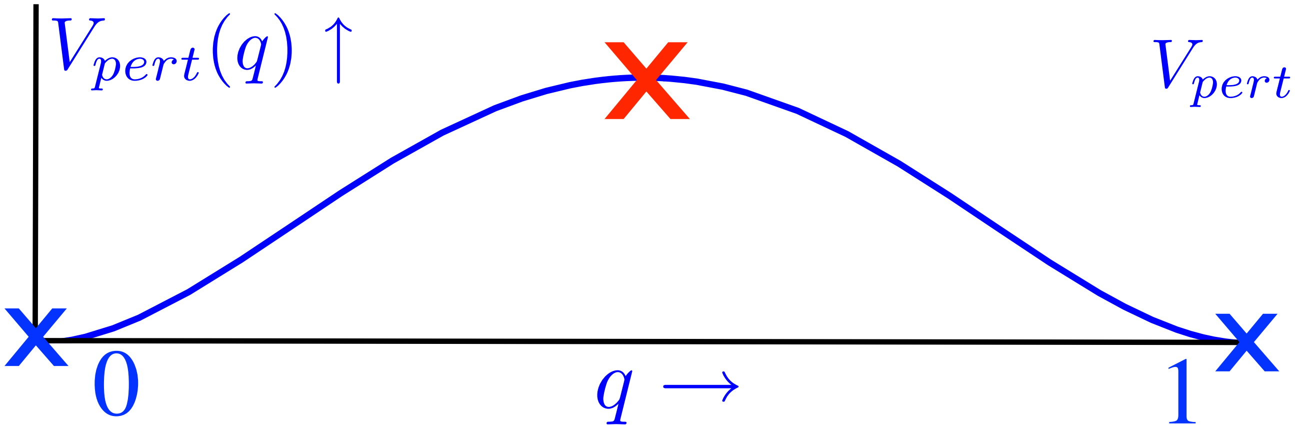

Point *half*way in between: q = ½ , $l$ = 0 .
Confined vacuum, $\mathbf{L}_c$,

$$\mathbf{L}_c = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$$

Classically, $A_0^{cl}$ has zero action: *no* potential for q.

# Potential for q, interface tension

Potential for q at one loop order: Gross, RDP, Yaffe, ‘81




$$V_{pert}(q) = \frac{4\pi^2}{3} T^4 \, q^2 (1-q)^2$$

Use $V_{pert}(q)$ to compute 't Hooft loop:

Bhattacharya, Gocksch, Korthals-Altes, RDP, ph/9205231.

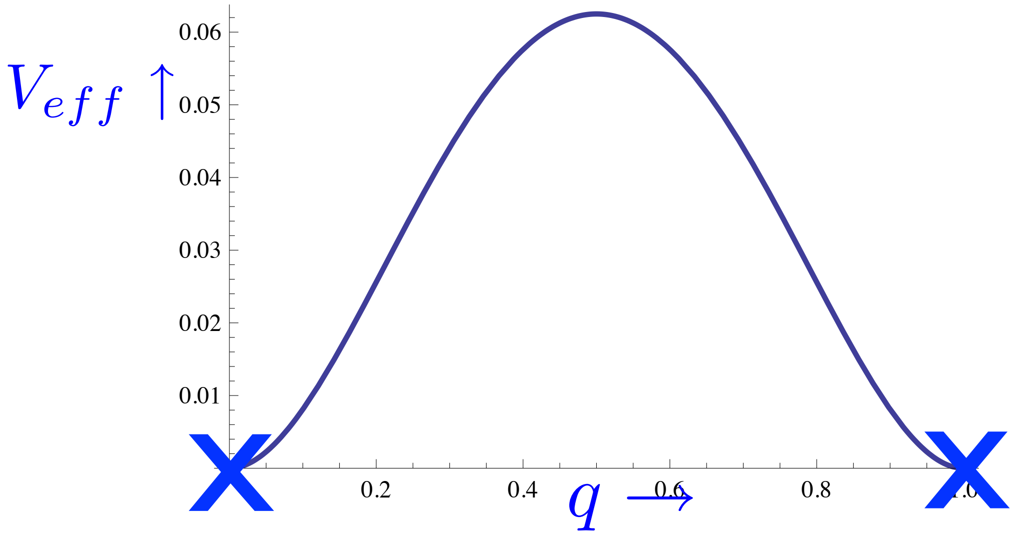
$$V_{tot}(q) = \frac{2\pi^2 T^2}{g^2} \left( \frac{dq}{dz} \right)^2 + V_{pert}(q) \qquad \Rightarrow \sigma = \frac{4\pi^2}{3\sqrt{6}} \, \frac{T^2}{\sqrt{g^2}}$$

# Cartoons of deconfinement

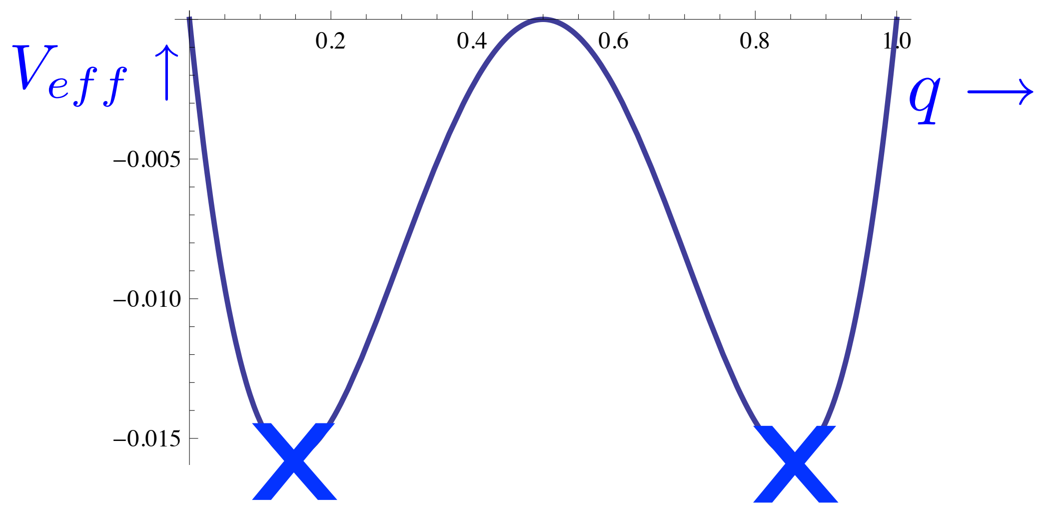
Consider:

$$V_{eff} = q^2(1-q)^2 - \; a\, q(1-q)\,, \; a \sim T_c^2/T^2$$

$\Downarrow$ a = 0: complete QGP



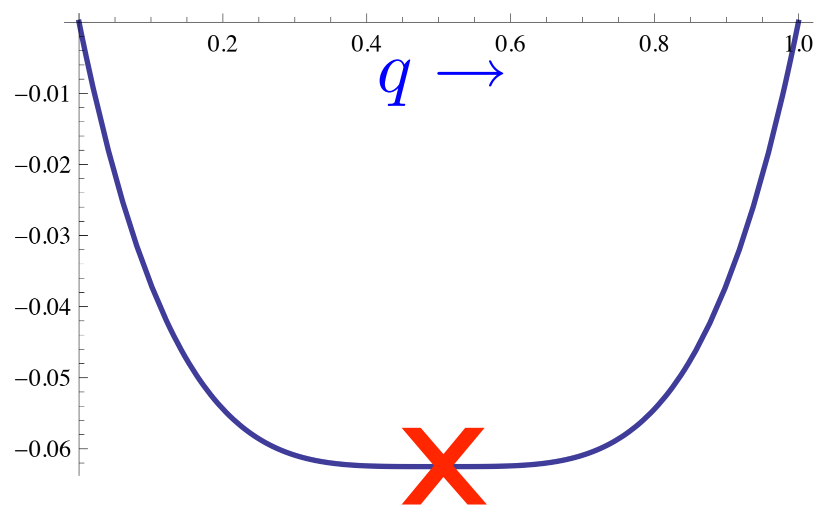

$\Downarrow$ a = ¼: semi QGP




a = ½: $\mathrm{T_c}$=>

Stable vacuum at q = ½

Transition *second* order



# Matrix model: N = 3

At infinite N, constant $A_0$ is the "master field" for the semi-QGP

Matrix model: implicitly, expansion in large N

Effective Lagrangian? *Only* from the lattice

N.B.: matrix model gives a first order transition for *all* N $\geq$ 3

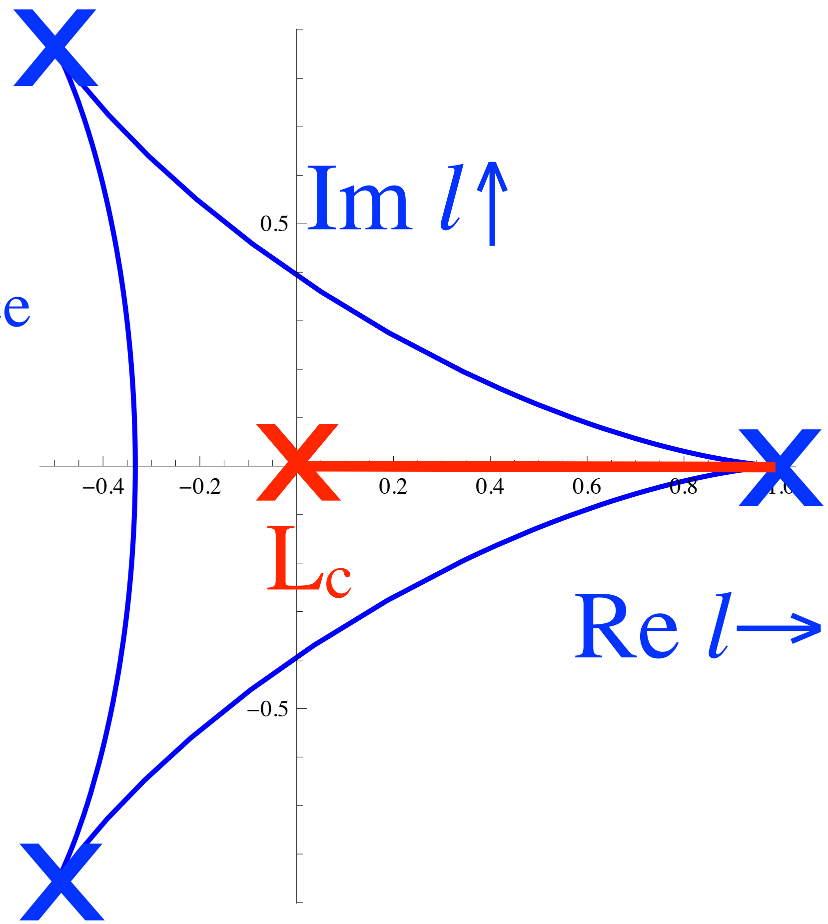
A. Dumitru, Y. Guo, Y. Hidaka, C. Korthals-Altes & RDP, 1205.0137

# Confining vacuum in SU(3)

Consider path along $\lambda_3 = \mathrm{diag}(1,-1,0)$:
When $q_3 = 1$:

$$\mathbf{L} = \mathrm{e}^{2\pi i q_3 \lambda_3/3}$$

$$\mathbf{L}_c = \begin{pmatrix} \mathrm{e}^{2\pi i/3} & 0 & 0 \\ 0 & \mathrm{e}^{-2\pi i/3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$




Elements of $\mathrm{e}^{2\pi i/3}$ $\mathbf{L}_c$ *same* as those of $\mathbf{L}_c$. Hence

$$\mathrm{tr}\,\mathbf{L}_c = \mathrm{tr}\,\mathbf{L}_c^2 = 0$$

$\mathbf{L}_c$ is the confining vacuum, **x**:
"*center*" of space in $\lambda_3$ and $\lambda_8 = \mathrm{diag}(1,1,-2)$

Move from deconfined vacuum, $\mathbf{L} = \mathbf{1}$,
to the confined vacua, $\mathbf{L}_c$, along red line:

# Matrix model: details

*Simplest* ansatz: constant, diagonal $A_0$:

$$A_0^{ij} = \frac{2\pi T}{g}\, q_i\, \delta^{ij}\ ,\ i,j = 1 \ldots N$$

At 1-loop order, perturbative potential

$$V_{pert}(q) = \frac{2\pi^2}{3}\, T^4 \left( -\frac{4}{15}(N^2-1) + \sum_{i,j} q_{ij}^2 (1-q_{ij})^2 \right)\ ,\ q_{ij} = |q_i - q_j|$$

*Assume* non-perturbative potential ~ $T^2\, T_c^2$:

$$V_{non}(q) = \frac{2\pi^2}{3}\, T^2 T_c^2 \,(-\frac{c_1}{5} \sum_{i,j} q_{ij}(1-q_{ij}) - c_2 \sum_{i,j} q_{ij}^2 (1-q_{ij})^2 + \frac{4}{15}\, c_3) + B T_c^4$$

For SU(N), $\Sigma_{j=1 \ldots N}\, q_j = 0$. Hence N-1 independent $q_j$'s, # diagonal generators.
Two conditions: transition occurs at $T_c$, and pressure = 0 at $T_c$. Can do better!

# Matrix model: parameters from the lattice

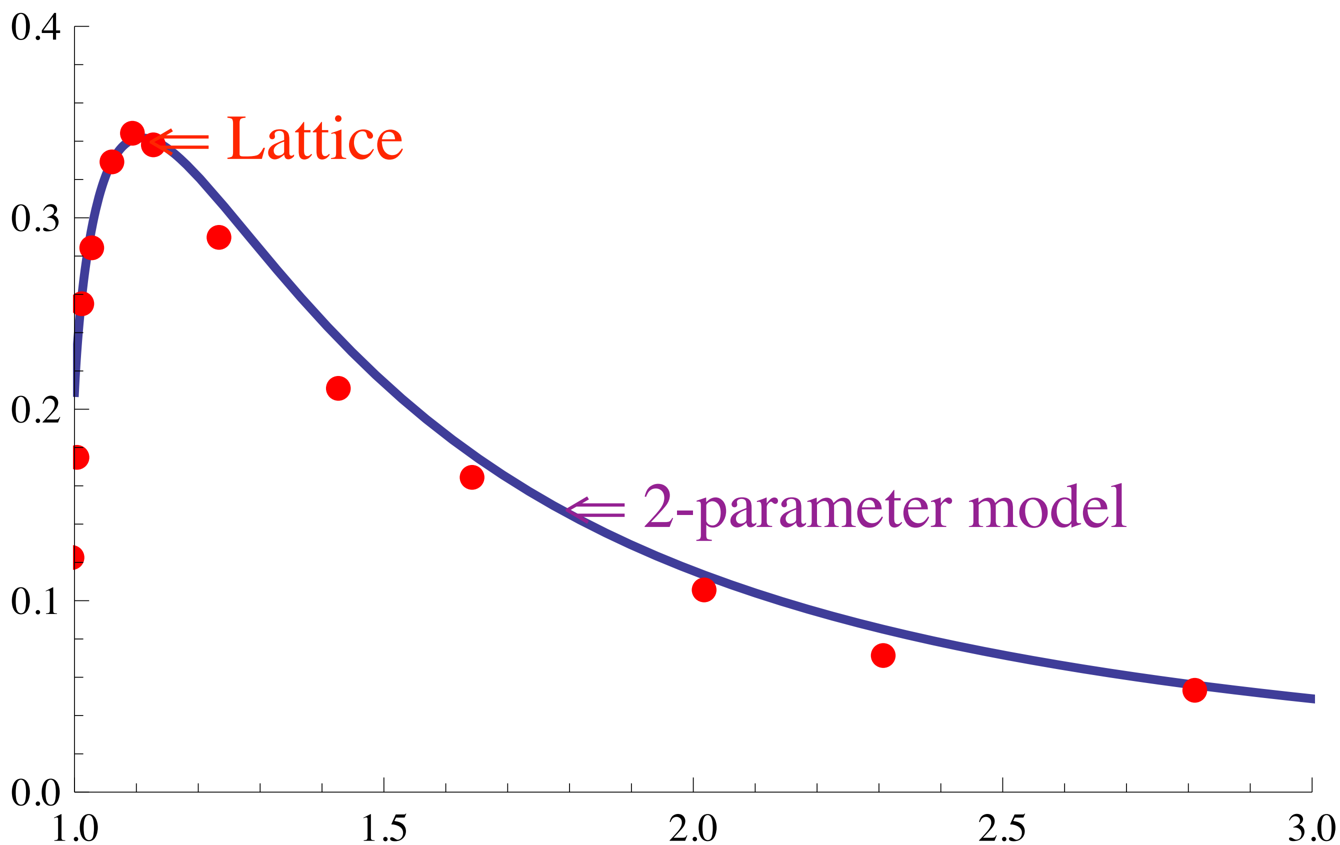
Choose 2 free parameters to fit:
latent heat at $T_c$, $(e-3p)/T^4$ at large T

$c_1 = .88$, $c_2 = .55$, $c_3 = .95$

Reasonable value for bag constant B:

$T_c = 270$ MeV, B~ $(262\ \text{MeV})^4$

$\dfrac{e-3p}{8\,T^4}\uparrow$



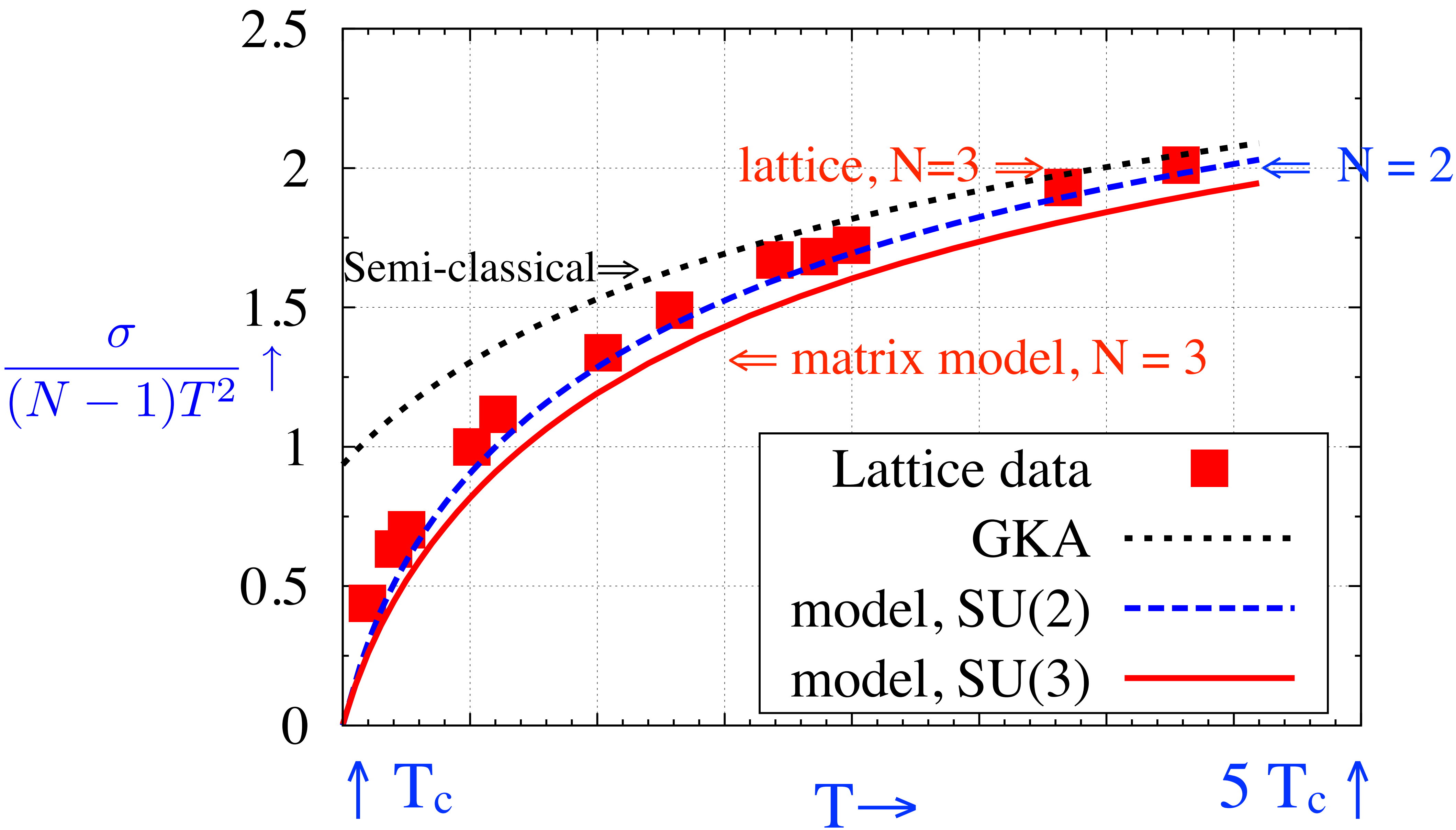

↑ $T_c$  $T/T_c$⟶  $3T_c$ ↑

Latent heat, lattice:
BPK: Beinlich, Peikert, Karsch
lat/9608141
DG: Datta, Gupta
1006.0938

# Matrix model: ‘t Hooft loop vs lattice

Matrix model works well:

Lattice: de Forcrand, D’Elia, & Pepe, lat/0007034; de Forcrand & Noth lat/0506005

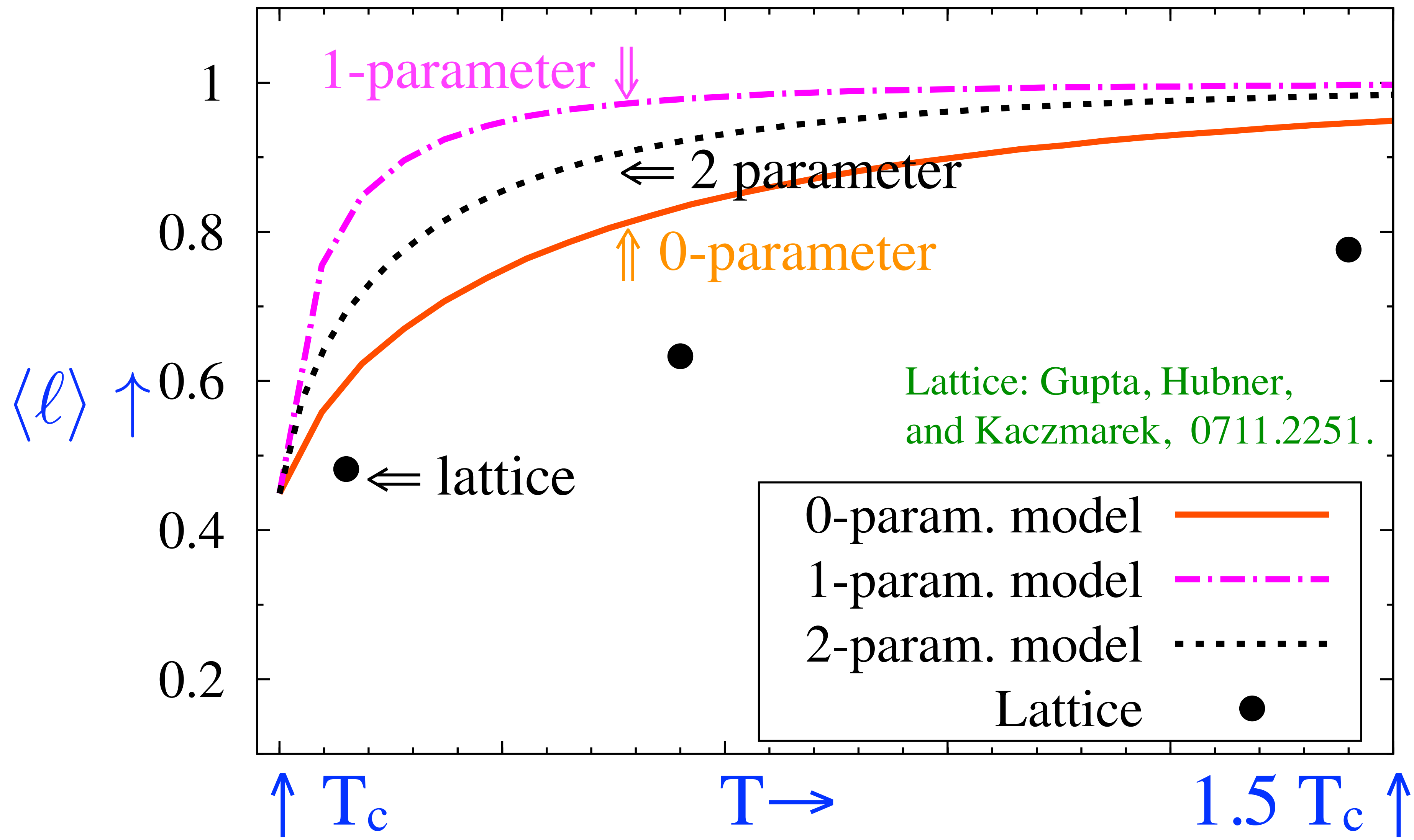


# Matrix model: Polyakov loop vs lattice

*Renormalized* Polyakov loop from lattice *nothing* like Matrix Model

Model: transition region *narrow*, to ~ 1.2 $T_c$. Lattice: loop *wide*, to ~ 4.0 $T_c$.

Can alter parameters to fit Polyakov loop; do not fit latent heat with 2 parameters



# Heavy quarks in the matrix model

## Position of the deconfining critical endpoint

Kashiwa, RDP, & Skokov 1205.0545

# Adding heavy quarks

Quarks add to the perturbative q-potential,

$$V^{qk}_{pert}(q) = -\,\mathrm{tr}\;\log(\not{D}^{cl} + m) \sim -\frac{\sqrt{2}}{\pi^{3/2}}\, T^{5/2} m^{3/2}\, \mathrm{e}^{-m/T}\, \mathrm{Re\,tr}\,\mathbf{L} + \ldots$$

Plus terms ~ $e^{-2m/T}$ Re tr $\mathbf{L}^2$, etc. Quarks act like background Z(3) field.
Heavy quarks wash out deconfinement at Deconfining Critical Endpoint, DCE.

For the DCE, first term works to ~ 1% for all quantities.

Add $V^{qk}_{pert}(q)$ to the gluon potential, and change *nothing* else, same $T_c$ .

Most straightforward approach. Naturally, $T_{DCE} < T_c$.

N.B.: Quarks generate v.e.v for $\langle loop \rangle$ below $T_c$, and so become sensitive to details of pressure in the confined phase. Have to modify the potential by hand to avoid unphysical behavior (negative pressure)

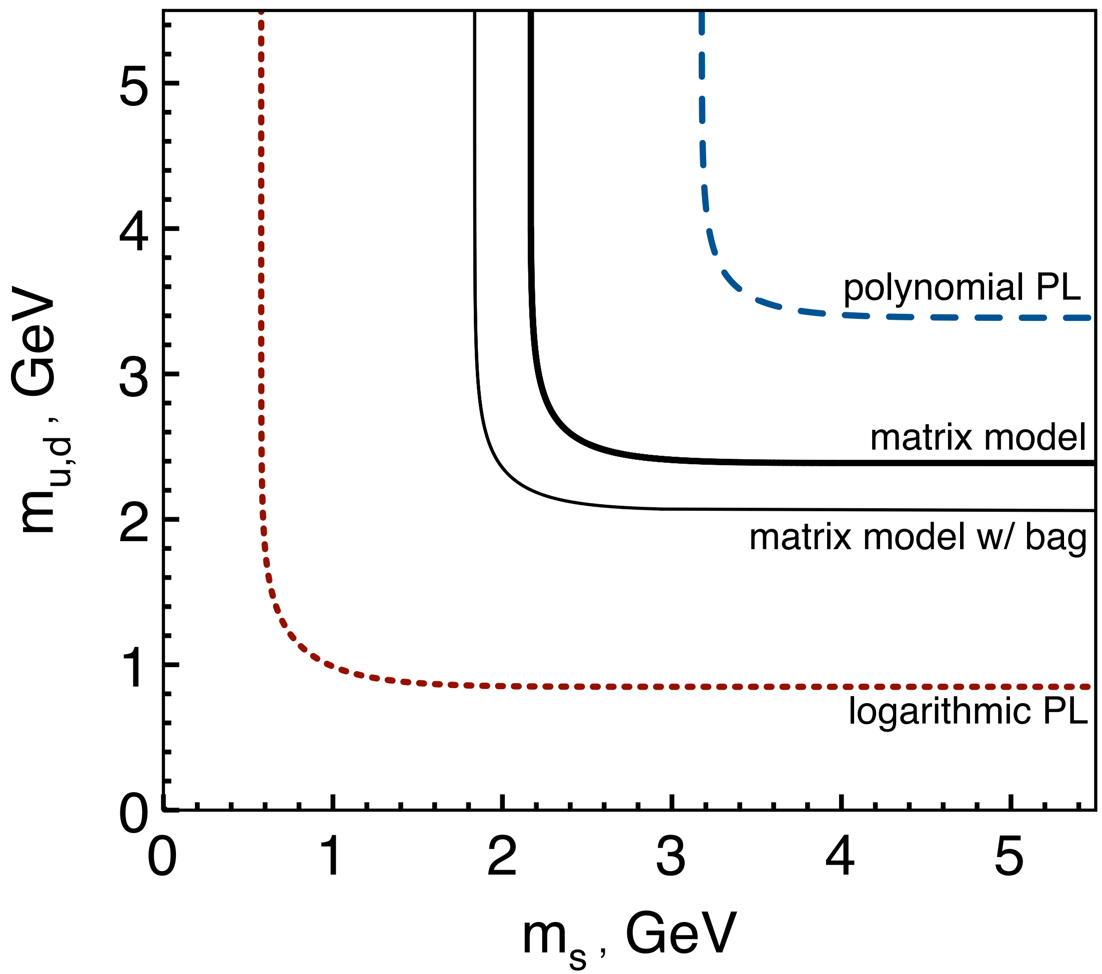
# Deconfining critical endpoint in matrix model

Matrix model: $T_{DCE} \sim 0.991\ T_c$ $m_{DCE} \sim 2.4$ GeV heavy

Lattice: $T_{DCE} \sim 0.998\ T_c$ $m_{DCE} \sim 2.2$ GeV

hopping parameter expansion: Fromm, Langelage, Lottini, Philipsen, 1111.4953

Polyakov loop models: $T_{DCE} \sim 0.90\ T_c$ $m_{DCE} \sim 1$ GeV << lattice result

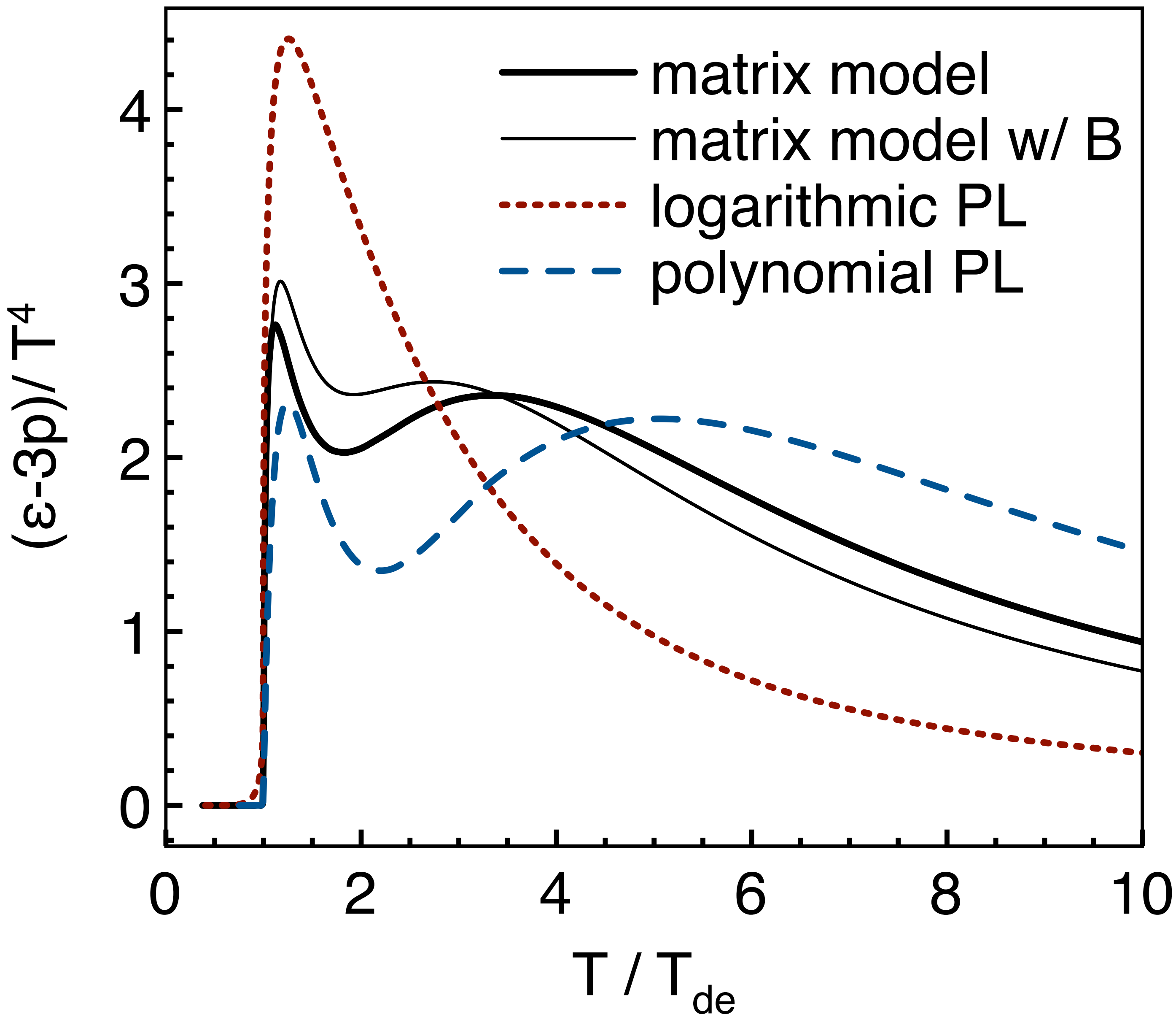


# Matrix model: prediction for interaction measure

For three flavors, matrix model gives two bumps in $(e\text{-}3p)/T^4$

One just above $T_{DCE}$ from gluons, another at ~ 4 $T_{DCE}$, from quarks.

Due to heavy $m_{DCE}$ . Does not happen for models with light $m_{DCE}$



# Matrix model for SU(∞)

Novel phase transition, Gross-Witten-Wadia

At infinite N, transition has aspects of both first *and* second order

E.g.: all interface tensions *vanish* at $T_c$

RDP & Skokov, 1206.1329; Lin, RDP, & Skokov, 1301.7432

# Matrix model at infinite N

Use eigenvalue density, $\varrho(q)$: $A^0_i \sim q_i$, $i = 1 \ldots N$, discrete sum $\Sigma_i \Rightarrow \int dq\, \varrho(q)$

$$V_n(q) = \int dq \int dq' \; \rho(q)\; \rho(q')\; |q - q'|^n (1 - |q - q'|)^n$$

Matrix model: $V_1$ and $V_2$. Take derivatives of equation of motion, at $T_c$ solution

$$\rho(q) = 1 + \; \cos(2\pi\, q) \;\;,\;\; q : -1/2 \rightarrow 1/2$$

Solution similar when $T \neq T_c$, $\varrho(q) = 1 + b \cos(d\, q)$.

Consider SU(N) on femtosphere: spatial sphere so small that coupling is small

Sundberg, th/9908001; Aharony, Marsano, Minwalla, Papadodimas, Van Raamsdonk, th/0310285; Dumitru, Lenaghan, RDP, ph/0410294

Effective theory for the spatially static model includes Vandermonde determinant

$$\# \left| \int dq\, \rho(q)\; e^{2\pi i\, q} \right|^2 + \int dq \int dq' \; \rho(q)\; \rho(q') \log |e^{2\pi i q} - e^{2\pi i q'}|$$

At $T_c$, eigenvalue density for the two matrix models are *identical:* not for $T \neq T_c$.

# Gross-Witten-Wadia transition at infinite N

Solution at N=$\infty$: "critical first order" transition - both first *and* second order

Latent heat *non*zero ~ $N^2$. *And* specific heat diverges, $C_v \sim 1/(T-T_c)^{3/5}$

Potential function of *all* tr $\mathbf{L}^n$, n = 1, 2.... But at $T_c^+$, only first loop is nonzero:

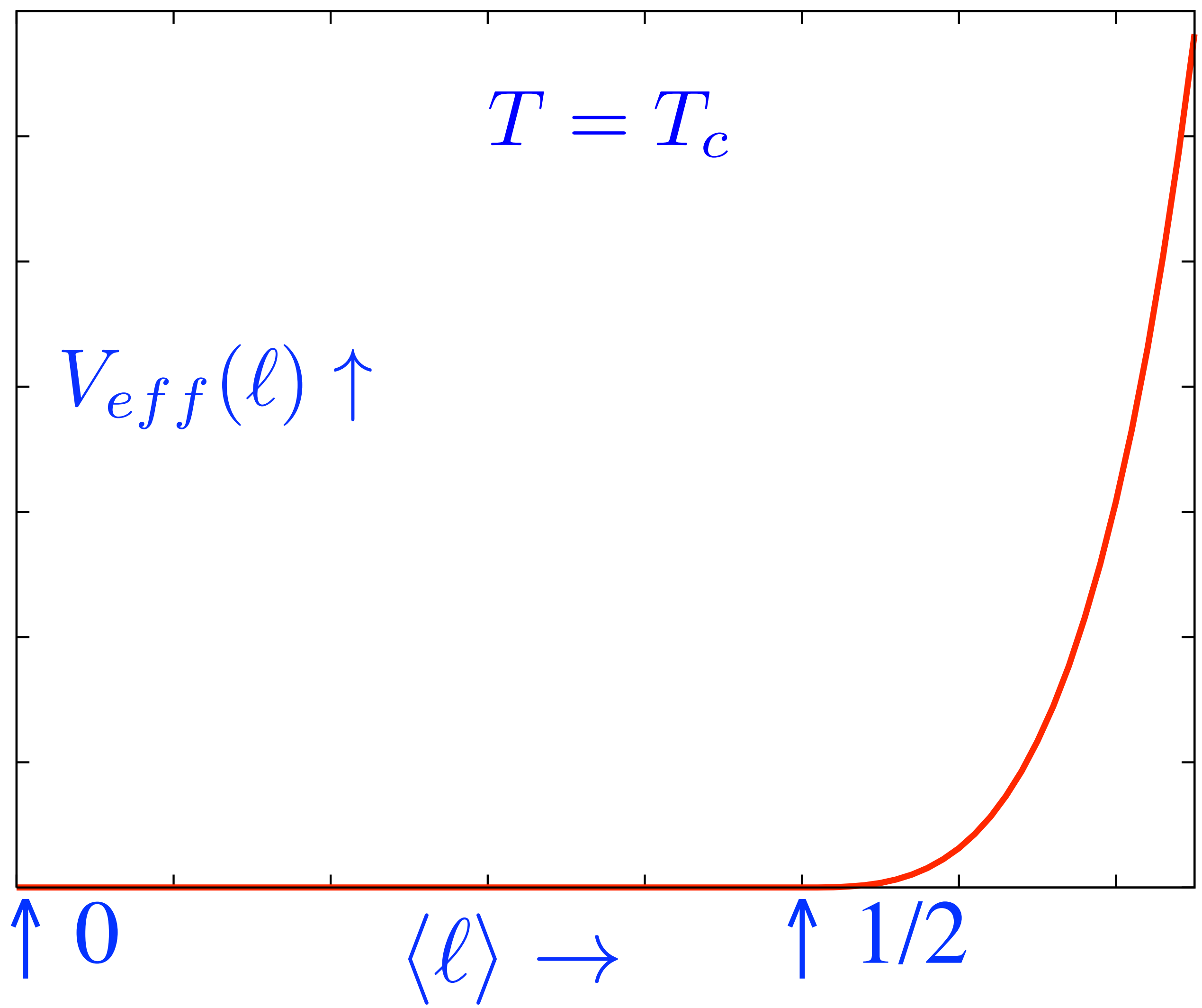
$$\ell = \frac{1}{N}\,\mathrm{tr}\,\mathbf{L}$$

$$\ell(T_c^-) = 0$$

$$\ell(T_c^+) = \frac{1}{2}$$

But $V_{eff}$ *flat* between them!

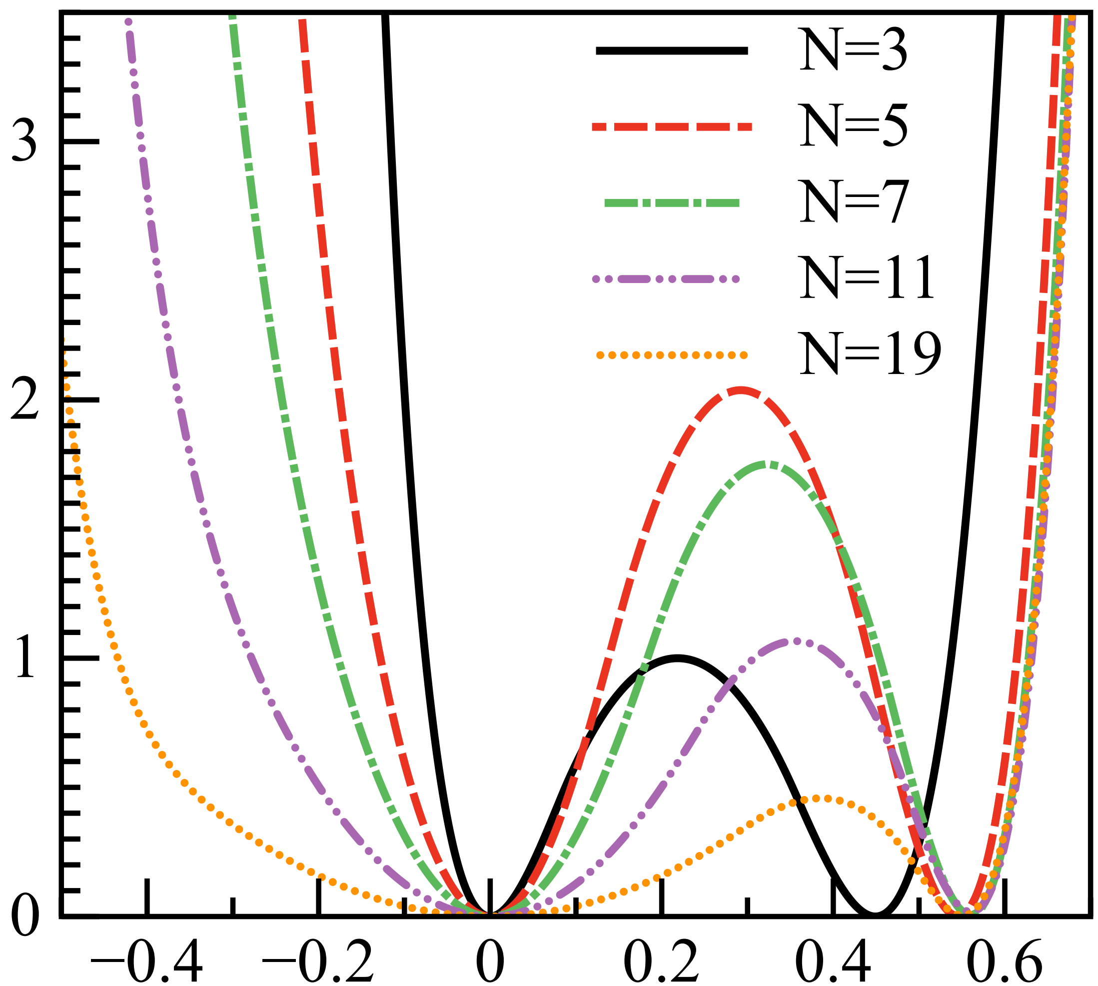
tr $\mathbf{L}^n$ $(T_c) = 0$ , $n \geq 2$



# Remnants of GWW at finite N

Solve matrix model numerically at finite N. Find two minima, at 0 and ~ 1/2.
Standard first order transition, with barrier & so interface tension, between them
Barrier disappears at infinite N: so interface tensions *vanish* at infinite N
Below: potential /($N^2$-1), versus tr **L** .

$$\frac{V_{eff}(\ell)}{N^2-1} \uparrow$$




$\langle \ell \rangle \rightarrow$

$0 \uparrow$ L $\uparrow 1/2$

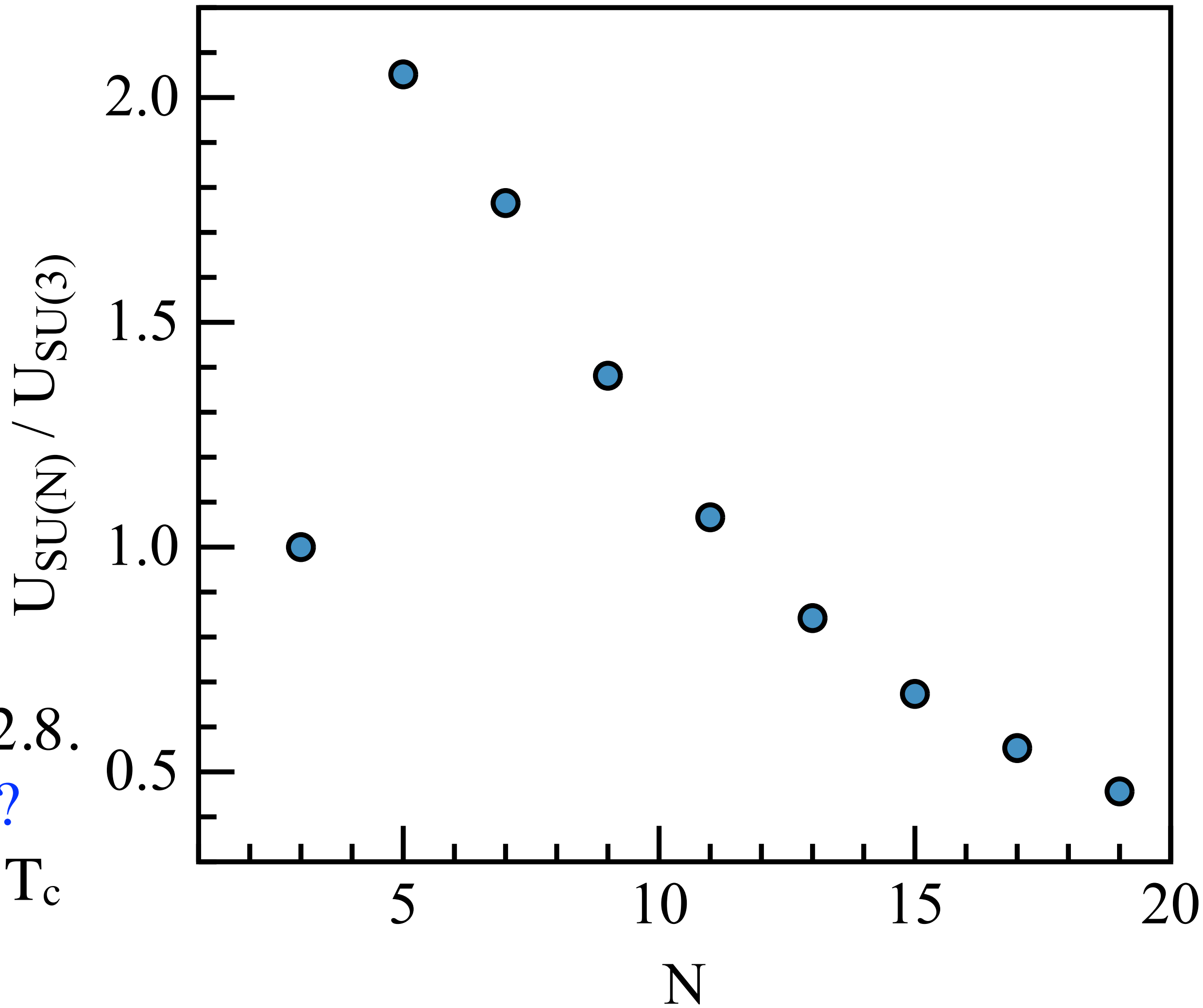
# GWW at finite N: interface tensions small at $T_c$

Consider maximum of previous figure, versus number of colors:
increases by ~ 2 from N = 3 to 5, then *decreases* monotonically as N increases
Perhaps: non-monotonic behavior of order-disorder interface tension with N?

Lattice: order-disorder interface tension $\alpha^{od}$ at $T_c$:
Lucini, Teper, Wegner, lat/0502003

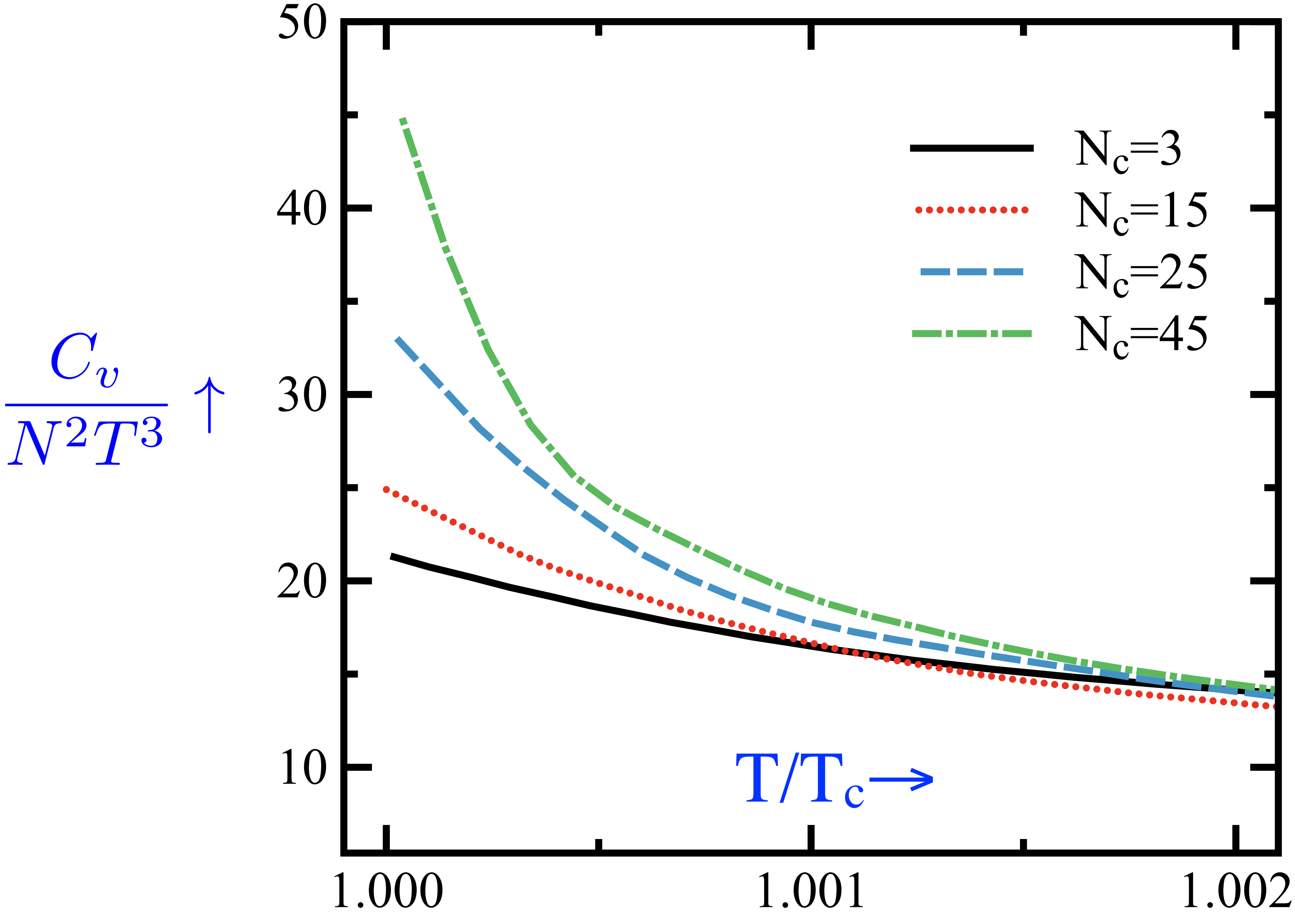
$$\frac{\alpha^{od}}{N^2 T_c^3} = .014 - \frac{.10}{N^2}$$

Coefficients *small*, $\chi^2$ *large*, ~ 2.8.
Sign of non-monotonic $\alpha^{od}/N^2$?
N.B.: 't Hooft loops *small* near $T_c$



# GWW at finite N: specific heat

See increase in specific heat only *very* near $T_c$, ~ .1 %, for *very* large N > 40



# Roberge-Weiss transitions

Value of an imaginary quark chemical potential, $\phi$:

How to measure the 't Hooft loop with *dynamical* quarks

Phase diagram in the T - $\phi$ plane for heavy quarks

Kashiwa & RDP, 1301.5344

# Roberge-Weiss symmetry

Quarks with *imaginary* chemical potential, $\mu = 2\,\pi\, i\, \phi\, T$.

Under global Z(N) rotation:

$$q(\vec{x}, 1/T) = \mathrm{e}^{2\pi i(\phi + 1/N)} q(\vec{x}, 0)$$

With quarks, and without $\phi$, no Z(N) symmetry.

With $\phi$, Roberge-Weiss symmetry:

$$\phi \to \phi + \frac{1}{N}$$

Periodicity occurs because of a phase transition, of first order, at $\phi_{RW} = 1/(2N)$ .

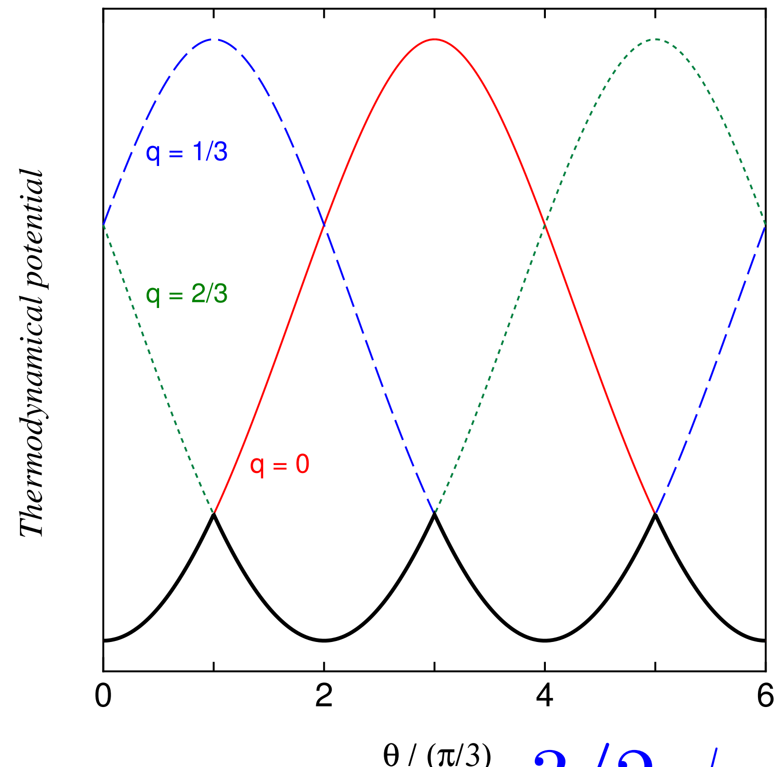
Jump from $A_0 = 0$, just left of $\phi_{RW}$ , to

$$A_0 = \frac{2\pi T}{g}\,\frac{1}{N}\,\mathrm{diag}(1 \ldots 1, -(N-1))$$

just right of $\phi_{RW}$ .

Boundary conditions *identical* to Z(N) interface.

Interface tension for 1st order transition at $\phi_{RW}$ is the 't Hooft loop - *with* dynamical quarks.




$3/2\ \phi \to$

# Phase diagram for RW transitions: high mass

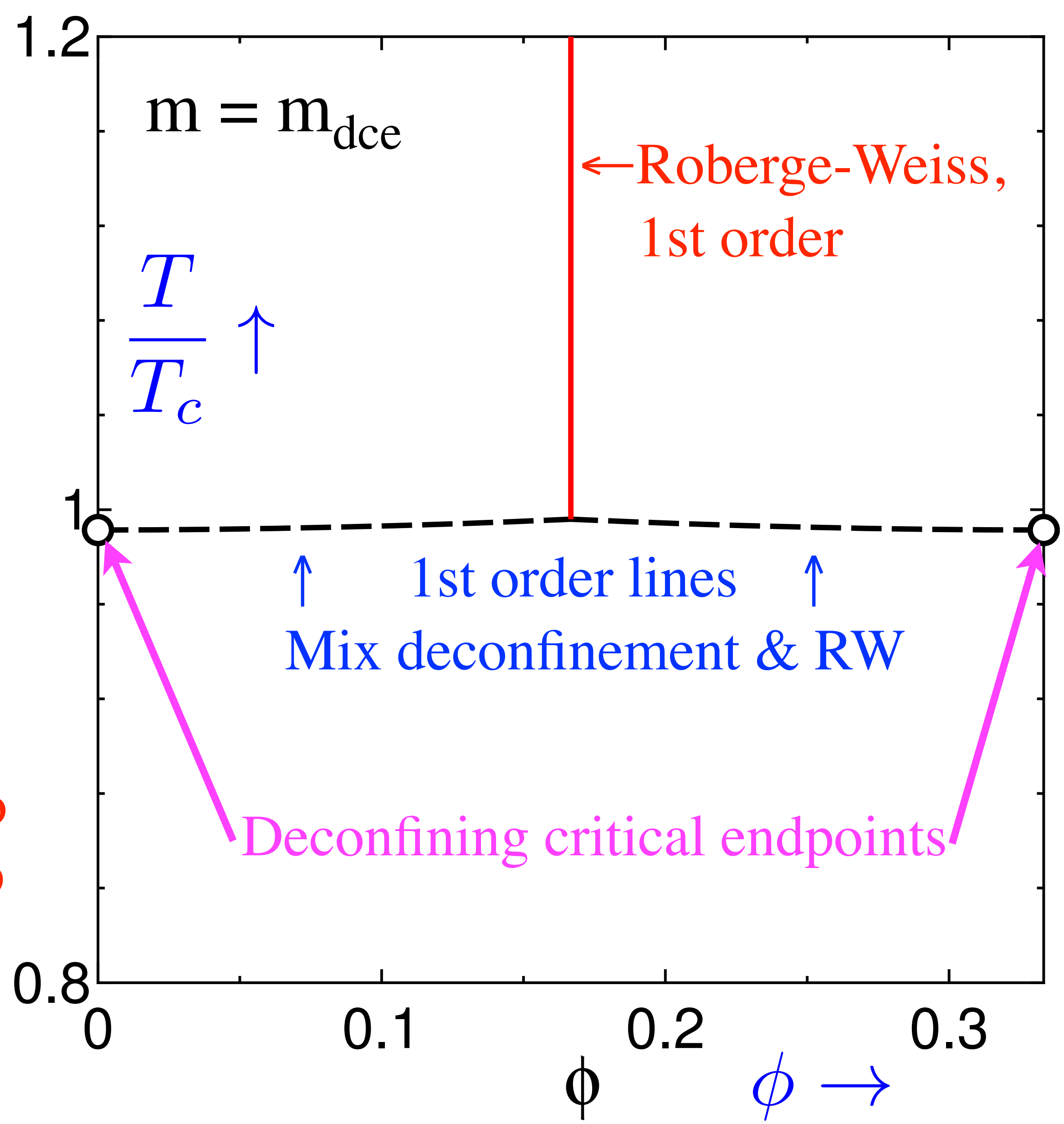
Above only for high T. Near $T_c$, use matrix model for heavy quarks

Consider $m = m_{DCE}$, at Deconfining Critical Endpoint

For high T, line of 1st order RW transitions at $\phi_{RW} = 1/6$: interface tension = 't Hooft loop

$\phi = 0$: 2nd order trans. in T, DCE

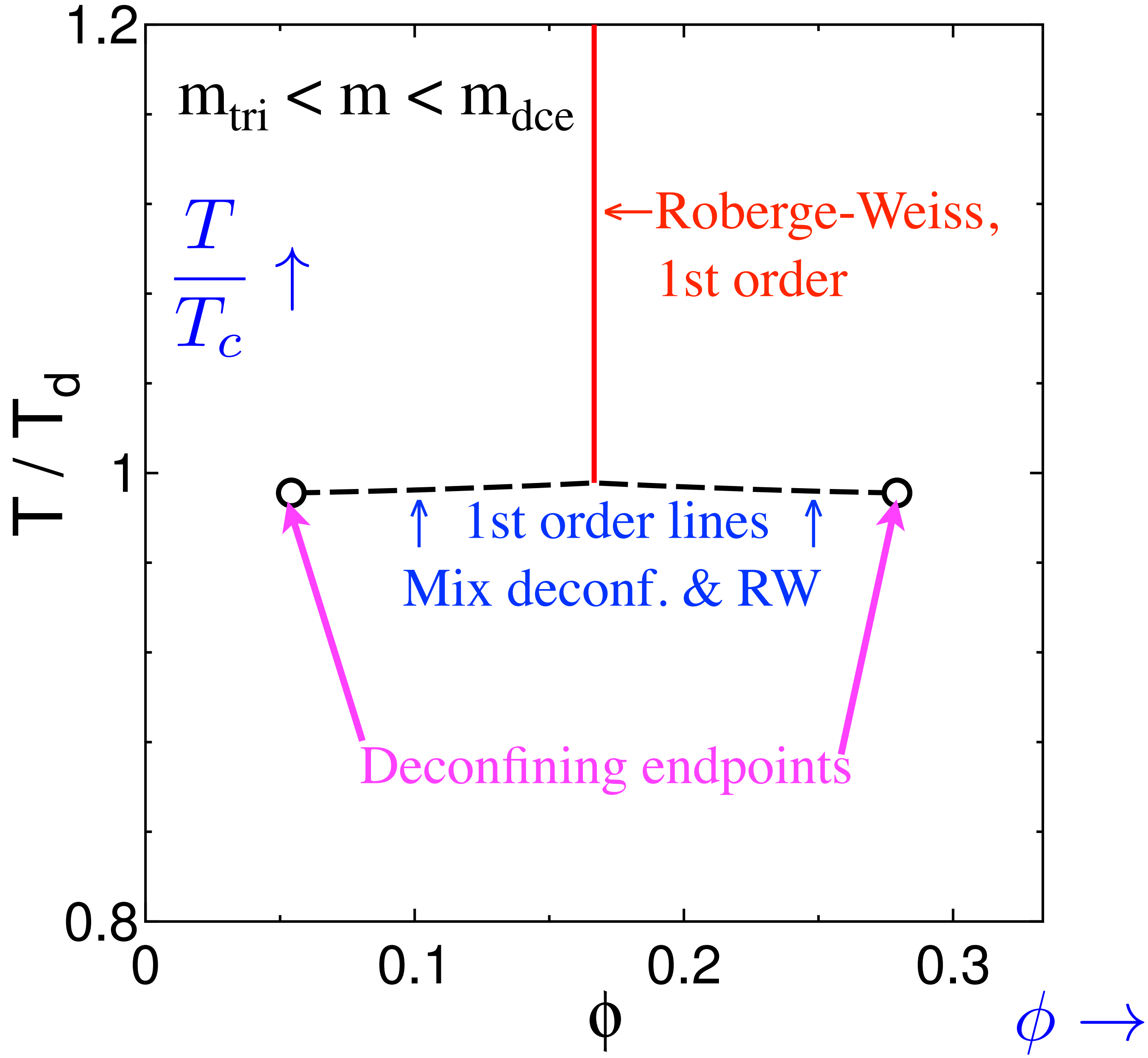
$\phi_{RW} > \phi > 0$:
Two lines of 1st order trans.'s
Mix deconfinement & RW
Jump in $A_0$ *not* Z(3) transform, so interface tension *not* 't Hooft loop



# Phase diagram for RW transitions: intermediate mass

$m_{dce} > m > m_{tri}$: lines of 1st order transitions shrink in $\phi$.

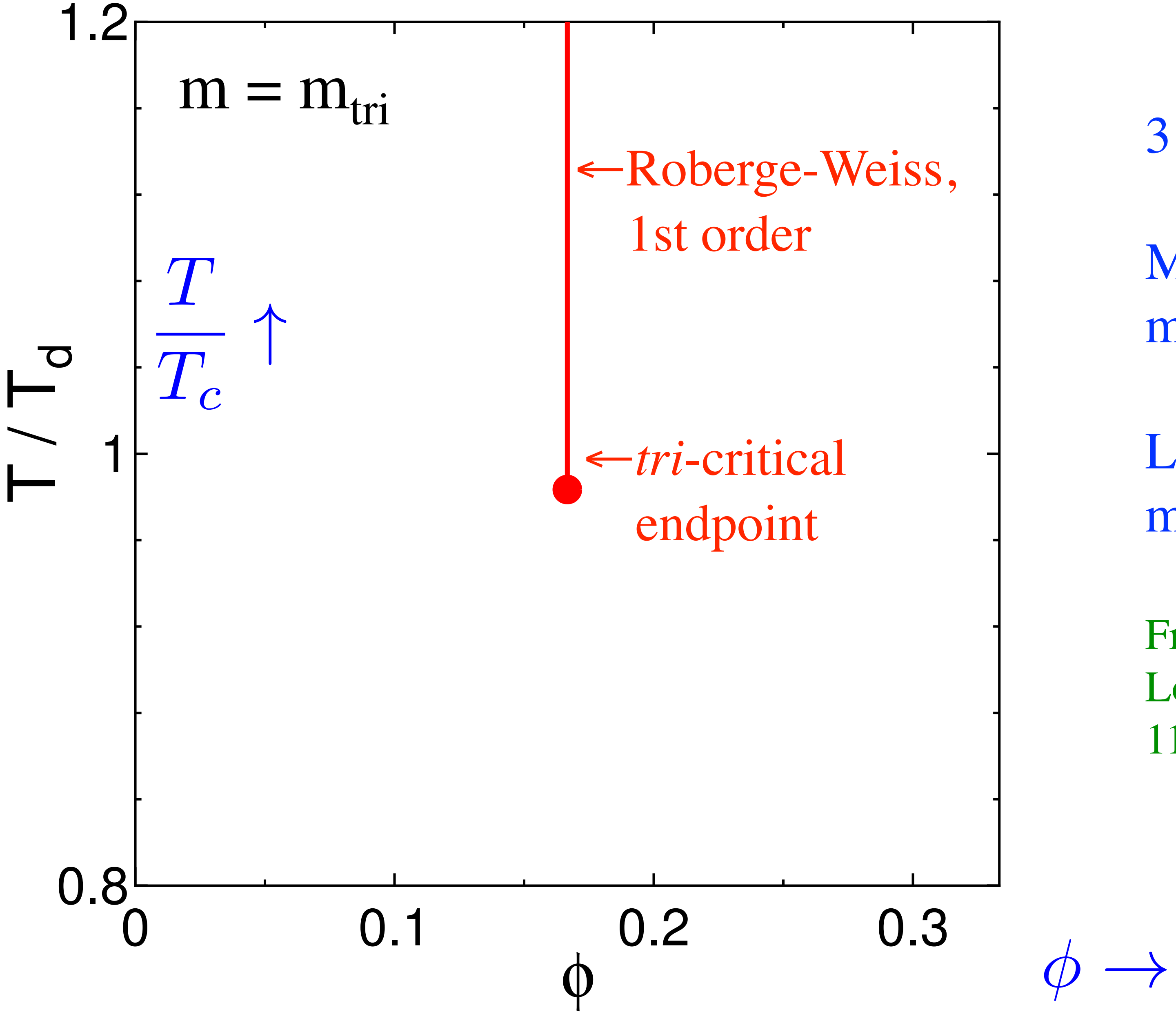
Again, interface tension = 't Hooft loop only for $\phi_{RW} = 1/6$



# Phase diagram for RW transitions: low mass

At $m = m_{tri}$, 1st order lines for $\phi \neq \phi_{RW}$ merge into $\phi_{RW}$, giving *tri*-critical point

For $m < m_{tri}$, line of RW transitions ends in an ordinary critical endpoint




3 degenerate flavors:

Matrix model:
$m_{tri} \sim 6.4\ T_{tri}$

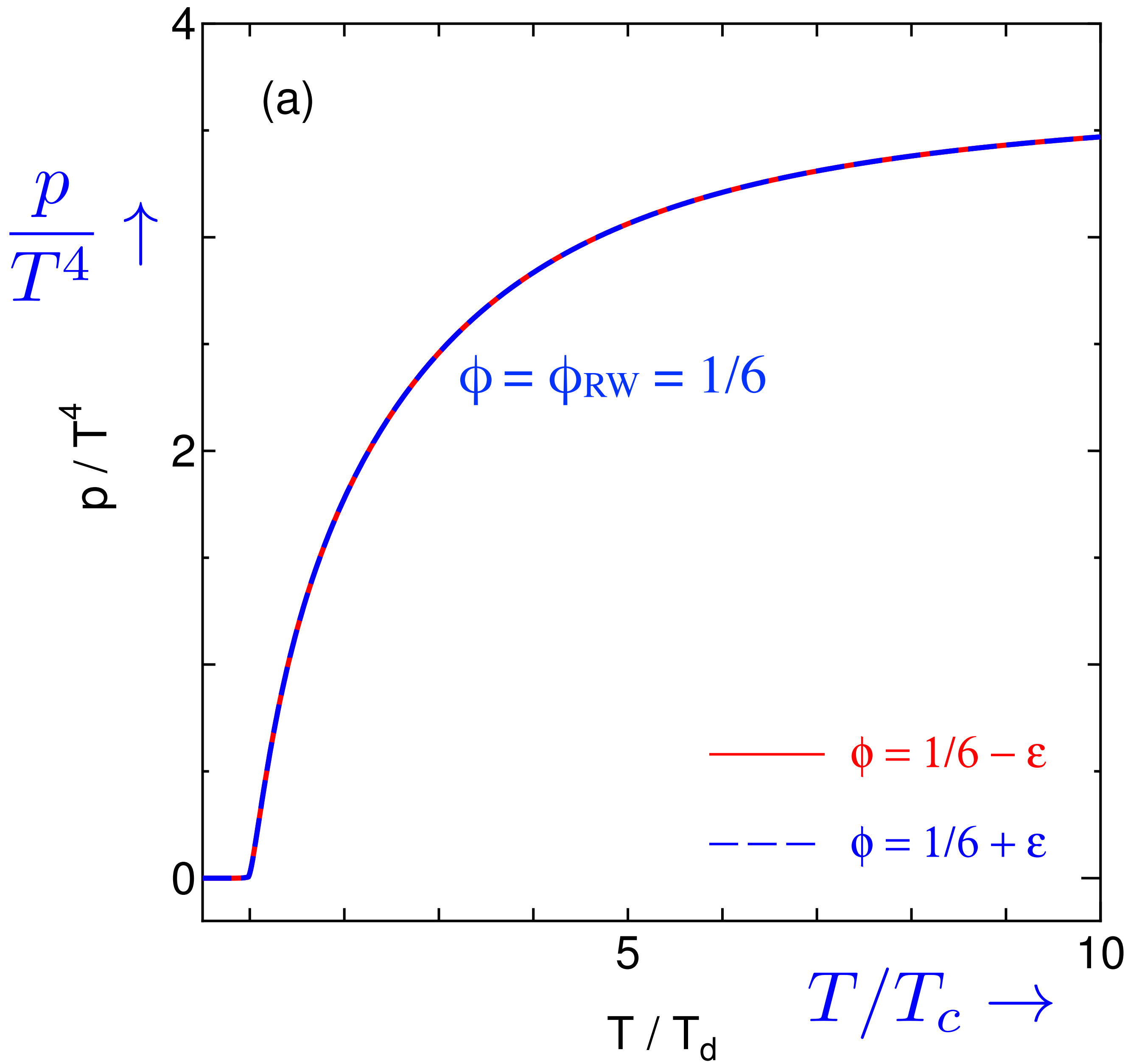
Lattice:
$m_{tri} \sim 6.7\ T_{tri}$

Fromm, Langelage, Lottini, Philipsen, 1111.4953

# Thermodynamics of Roberge-Weiss transition

Use matrix model to compute at $m=m_{dce}$ , $\phi = \phi_{RW} = 1/6$.

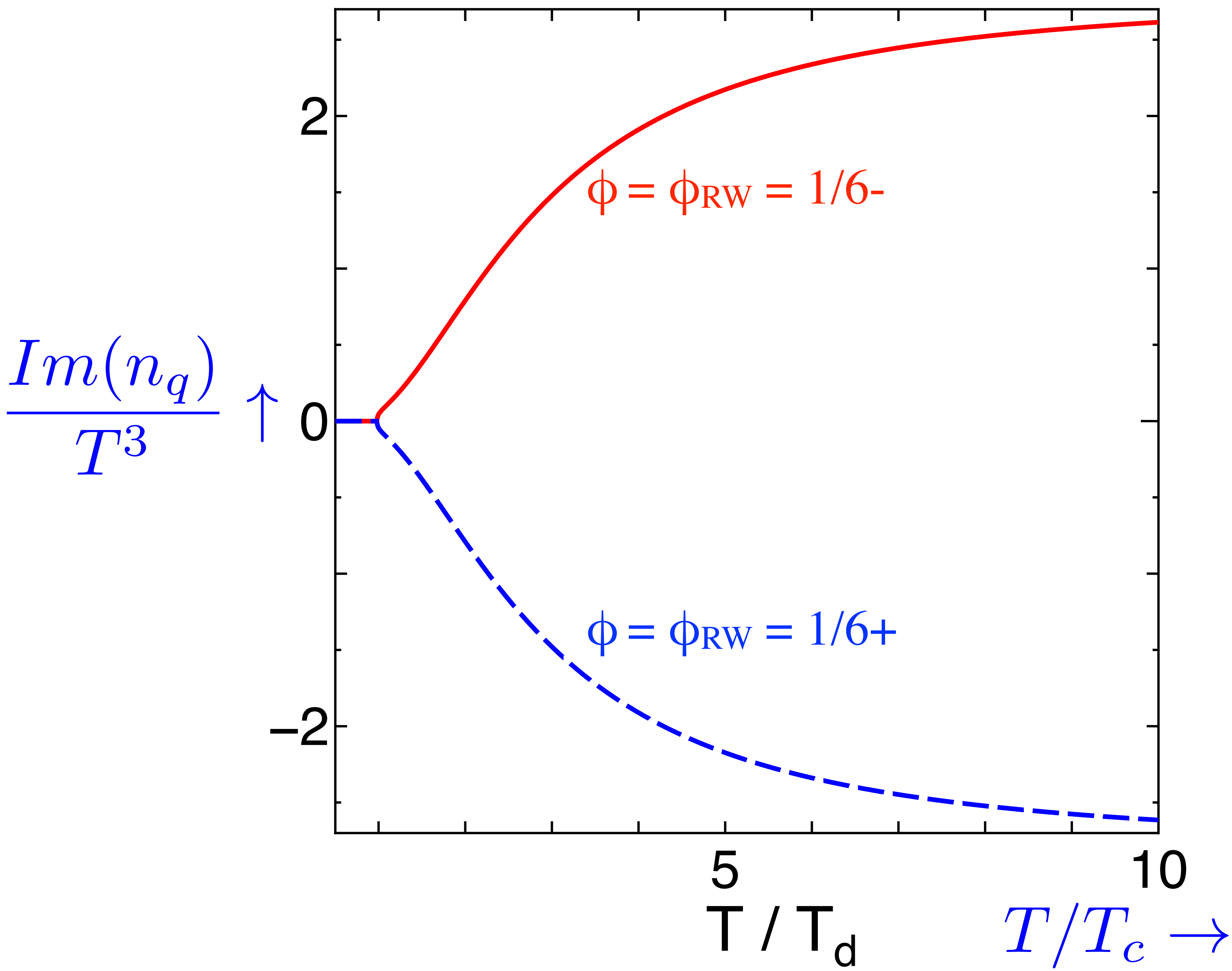
Pressure even in $\phi$, so doesn't change



# Quark number density at RW transition

Use matrix model to compute at $m_{dce}$ , $\phi = \phi_{RW} = 1/6$.

(Imaginary) part of quark number density odd in $\phi$, so flips sign

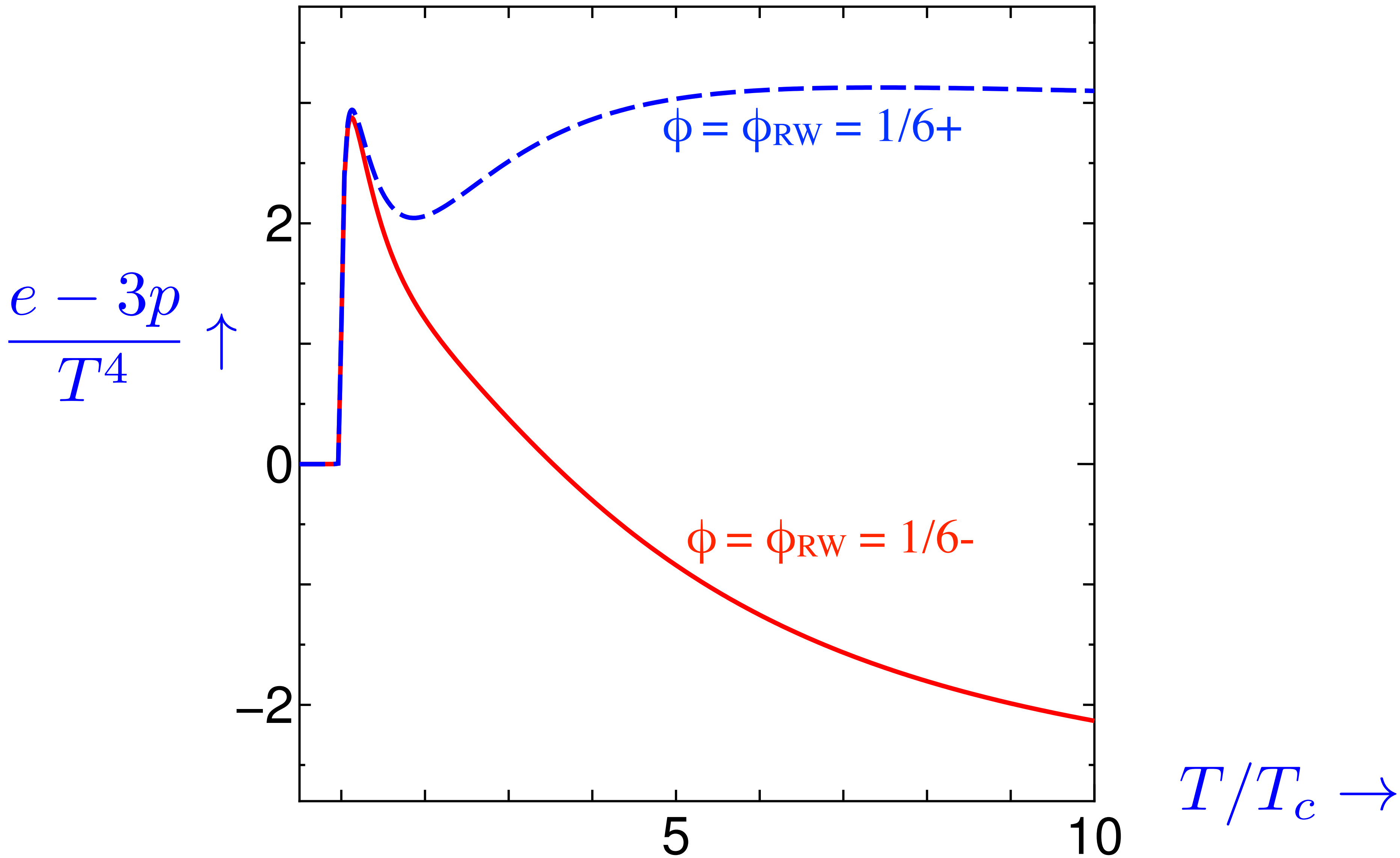


# Interaction measure at RW transition

Use matrix model to compute at $m_{dce}$ , $\phi = \phi_{RW} = 1/6$.

Energy density jumps at transition. Interaction measure *negative* to right of $\phi_{RW}$

Unphysical, occurs as chemical potential ~ T is imaginary



# Future work

Straightforward to add light quarks with chiral effective lagrangian.

In the matrix model, $T_{deconfinement} \neq T_{chiral}$ : $T_{chiral}$ *new* parameter

Standard kinetic theory:

To obtain small shear viscosity $\eta$, as $\eta \sim 1/g^4$ , coupling must be large

Then for radiative energy loss, qhat $\sim g^2$ is large

Majumder, Muller, & Wang, ph/0703082; Liao & Shuryak, 0810.4116...

Matrix model: $\eta$ small when the loop is (Y. Hidaka & RDP)

$\sigma \sim loop^2$, but $\varrho$ = density $\sim loop^2\, T^3$:

$$\eta \sim \frac{\rho^2}{\sigma} \sim \ell^2$$

Collisional energy loss $\sim \varrho_{quark} \sim loop$ , small near $T_c$.

Presently computing radiative energy loss, production of photons, dileptons...

Experiment? Both RHIC & LHC are mainly (all?) in the s-QGP.